A Review and Case Study of the Effect of Urbanisation on Streamflow

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A REVIEW
AND
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THE EFFECT OF
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STREAMFLOW
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by

R.F. FRASER, B.Sc.

Submitted in partial fulfillment of
the Master's Degree in Geography.

Wilfrid Laurier University
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1. INTRODUCTION.

To initiate the discussion it would be appropriate to consider the subdiscipline of Urban Hydrology. This field of research has been designated as the, "interdisciplinary science of water and its interrelationships with urban man," (Jones, 1971, p.258). The science of water, or hydrology, has only recently become an exact or physical discipline in which mathematical notation has been used to attempt to account for certain natural phenomena, in a similar manner in which physics progressed some centuries earlier. Yevjevich (1974) describes two major eras of determinism, in which hydrological phenomena were described deterministically rather than stochastically.

The first era, around the turn of the last century, began with the interest of geophysicists and geographers in hydrological phenomena by measuring those variables of the atmosphere, the earth's surface, and beneath the ground. This approximately coincided in time with the development of Fourier series analysis which attempted to fit trigonometric functions to sequential processes. This coincidence of interest in natural phenomena and the development of mathematical techniques was likely the reason that the deterministic approach for discovering periodicities in
hydrological time series gained popularity during the last
decades of the nineteenth century and the first few of the
twentieth century.

The second era of determinism is in full progress at
present. It is in the form of searching for deterministic
responses of hydrological environments either as analytical
functions, experimental curves, or empirical relationships.
Basically, it involves the search for deterministic
relations among the observed hydrological random variables.
This will become more apparent in the succeeding chapter,
the Literature Review.

Urban hydrology fits conveniently within the umbrella of
its father discipline, hydrology, but concentrates on the
rapidly evolving urban environment. As the world's
population expands at an ever increasing rate it is also
becoming more urbanised at an even faster pace. This change
from a formerly rural existence to a complex urban society
has increased most rapidly in the last several decades,
resulting in a vast centralisation of population into very
small areas. This centralisation has created a concentration
of escalating demands on man's surrounding environment,
which has in turn produced complex and diverse problems of
an economic, social, political, and physical nature. Within
the vast spectrum of problems of a physical nature those
which are water-related are considered in the realm of urban
hydrology.

Introduction 2
In 1969 an American Society of Civil Engineers (ASCE) Task Force Progress Report noted that such problems will become of even greater importance in the future. The urban population of USA may represent three-quarters of the total population by 1980, and possibly as much as four-fifths by 2000. Urban populations estimated at 193 million for 1980 and at 219 million for 2000 will occupy urban land areas of approximately 32 million and 45 million acres respectively. Thus, by the year 2000 urban land area in the USA has been estimated to be as little as 2.4% of the total area, illustrating that from the standpoint of the national land area the problem of urbanisation still appears to be relatively localised. However,

"it is in this limited land area that some 80% of our population will live and where the bulk of our economic wealth will be situated. Recognising that it is in the realm of protecting life and property that the flood control program operates, it is obvious that it is in this same limited land area that most flood control development will occur. Hence the need for greater insight and understanding of the effects of urban development on the flood flows against which protection must be provided," (Smith, 1969, p.289).

Unfortunately there is general agreement as to the lack of precise knowledge of urban water-related problems, including flood control,

"It quickly became apparent that remarkably little quantitative information was available on the broad implications of the effect of urbanisation on water resources management," (Schneider, 1975, p.450).
While, in July 1975, a workshop session held by the ASCE, was summarised by Whipple & Hufschmidt (1976) who stressed that, "Urban hydrology is much neglected" and expressed concern at the, "slow progress in solving metropolitan area water problems," (p. 762). Furthermore, it was suggested,

"The many and complex interactions of land and water in the urban setting some of which are only beginning to be identified, emphasise the importance of integrating, or at least co-ordinating the planning and management of water resources and land-use," (Whipple & Hufschmidt, 1976, p. 763).

McPherson (1972a) castigated this neglect stating that, "the field of urban hydrology is almost devoid of modern research investment," (p. 2), and also suggested that too few data have been collected to describe the effect of urban and suburban development on flood runoff. The ASCE initiated the Urban Water Resources Research Programme in 1969 to help redress the balance. This programme attempts a comprehensive research approach to all water-related problems within urban areas, one of the most important of which is flooding.

Engineers were the first to respond to the problems of alleviating urban flooding and transporting storm runoff, because of the constantly increasing cost of, and demand for adequate urban drainage. In USA, millions of dollars are being spent annually by federal, state, and local agencies, yet the engineering designs for these expenditures are often
of necessity based on meagre hydrologic data. For example, Los Angeles County spent $179 million on storm drains to relieve local flooding and still found that it needed additional drains costing about $1 billion to provide adequate relief from local floods and to protect as yet undeveloped areas. For the whole of USA the American Public Works Association (APWA) estimated the value of all those sewers already installed, at a 1965 construction cost level, at over $22 billion. Over the 1966-1969 period, the average annual cost was calculated to be $2,500 million; $1,300 million in deficiencies, obsolescence, and depreciation and $1,200 million in future growth, (extracted from tables in McPherson, 1969, p.161-162).

Despite this investment urban flooding is still a major concern; such that losses can range from such temporary disruptions as travel delays, power failures, and minor flooding to extensive damage of highly valuable property from inundation. Throughout the USA direct economic costs of urban flooding are estimated by the Corp. of Engineers at about $1 billion per annum, which increases to at least $1.6 billion if unobserved urban flood losses are accounted for. In total,
"it is easy to account for direct losses and expenditures amounting to more than $4 billion per annum, and these figures place no value on public inconvenience, interrupted or diminished productive capability, time losses, relief measures, or human misery," (Jones, 1971, p.263).

Although the engineering science dominates urban hydrology at the moment, the subject is rapidly becoming interdisciplinary. Recently there has been an increasing concentration of research on man's impact on his environment. Physical and resource geography has contributed, in part, to this development of the earth and environmental sciences. Within the urban environment the study of urban flooding has been developed mainly through the research of geomorphologists. This research has evolved through the applied or problem-oriented approach to environmental issues and resource evaluation. Chow (1967) declared that,

"for the wise management and intelligent use of water resources, there is a need to ascertain the magnitude and consequences of man's influence on the physical environment," (p.6).

For example, the physical characteristics of watersheds are continually being modified by man's changes in land-use, in this case, urban land-use. In fact, during UNESCO's research programme known as the International Hydrologic Decade (IHD) from 1965-1974, the influence of man on the hydrologic cycle was noted as one of the five major problem areas; stating that in regard to urban land-use,
"the replacement of wildlands or farmlands by massive constructions of a city is perhaps the most drastic of all large scale changes in land-use brought about by man," (UNESCO, 1972, p.55).

Upon reflection, the engineering approach concentrates on the different types of changes in streamflow that are caused by urbanisation, while the broader environmental approach tends to consider the effects of those streamflow changes on the urban landscape itself. Indeed as part of the latter approach, geographers with a traditional background in geomorphology and more particularly in fluvial geomorphology, when considering the urban hydrologic environment seem to have concentrated upon a number of specific areas. For example, Graf (1976) studied the changes in channel and flood plain configurations, while the changes in sediment loads and yields can be exemplified by a study carried out by Douglas (1974). Lastly, Hammer (1972) investigated the increase in channel cross-sections in relation to differing types of urban land-uses.

Finally, Chow (1967) stated that,

"Geography changes the nature of hydrologic problems as hydrologic regimes differ from one area to another. In assessing the priority of a hydrologic problem for investigation, the factor of geography must be considered in addition to other factors such as economic capability," (p.9).

In conclusion, the need for urban hydrologic research, particularly involving flood problems, is emphasised. Furthermore, the recent expansion in environmental sciences
has resulted in a common interdisciplinary concern in these problems, although particular research priorities from each discipline are evident. This study now reviews the research on the effect of urbanisation on streamflow in order to present a subsequent case study of the influence urbanisation exerts on streamflow, and can be included within the recently expanding interdisciplinary base of urban hydrology.
2. LITERATURE REVIEW.

In order to review the various themes covered by urban hydrologic studies researching the effect of urbanisation on streamflow a structure should be devised to facilitate this purpose.

Amorocho & Hart (1964) describe the study of the hydrologic cycle as being approached by two main paths, which characterise, in the final analysis, the basic motivation of the workers in the field. In the first case various research activities into the physical sciences have been pursued, dealing with phenomena related directly or indirectly to the hydrologic cycle. The aggregation of these studies Amorocho & Hart termed "physical hydrology", although the sciences involved are not generally confined to hydrologic problems alone. The primary motivation here is the study of the physical phenomena; generally the eventual practical application of this knowledge for engineering or other purposes is recognised but not explicitly sought. This covers the majority of urban hydrologic studies considered herein and which devote themselves to quantifying the effect of urbanisation on streamflow.

In the second case, a great deal of work has been carried out on the investigation of hydrologic systems for the explicit purpose of establishing quantitative
relationships between precipitation and runoff, which can be used for the reconstruction or prediction of flood sequences and watershed yields. Amorocho & Hart labelled this path as "systems investigations". Within urban hydrologic studies this can be seen to be concerned with the simulation or mathematical modelling of urban storm water runoff.

This review, however, concentrates upon the first path, "Physical Hydrology", in which Amorocho & Hart suggest the emphasis is centred upon topics or foci of study that consider hydrologic component phenomena and their relationships. By adopting this concept, research on the effect of urbanisation on streamflow may be reviewed in terms of the different components of streamflow that are altered by the presence of urbanisation. Thus, a series of major streamflow components may be considered in turn; each one concerned with a particular aspect of streamflow. Table 2.1 presents the major components that are reviewed; those being the time distribution, the peak discharge, and the runoff yield. Within the major components, more specific variables [1] are reviewed separately, particularly where they consider different aspects of the streamflow components. For example, within the peak discharge component, the Hydrograph Peak considers the changes in the peakflow of individual precipitation - runoff events and the Mean Annual Flood considers the changes in the flood peak that has a recurrence interval [2] of 2.33 years.

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<table>
<thead>
<tr>
<th>Time Distribution Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag Time Variable</td>
</tr>
<tr>
<td>Time of Rise Variable</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Discharge Component</th>
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</thead>
<tbody>
<tr>
<td>Hydrograph Peak Variable</td>
</tr>
<tr>
<td>Mean Annual Flood Variable</td>
</tr>
<tr>
<td>Low Flood Frequency Variable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Runoff Yield Component</th>
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</table>

After illustrating the changes that occur in different streamflow components because of the effects of urbanisation, some of the processes by which urbanisation actually induces those changes are considered. Finally, some of the methods that have been devised to measure urbanisation within a catchment are discussed.
2.1 Changes in Streamflow Components.

Studies concerned with the effect of urbanisation on streamflow characteristics suggest that the surface flows from urbanised areas differ from "natural" areas in several ways [3]. These may be identified as changes in:

a) total quantity or yield;

b) timing and distribution of flows, as shown by the hydrograph shape;

c) characteristics of basin discharge, as well as changes caused by external influences, (Waananen, 1969, p.170-171).

The majority of research considering these differences has been carried out in the USA, when as early as 1954 the Texas District of the Water Resources Division of the Geological Survey began its urban hydrology studies with the Waller Creek project. This project was established to provide rainfall and runoff data to define the effects of progressive urbanisation on peak flows and the rainfall-runoff relation, (Schneider, 1969). To evaluate the changes quoted above a number of different, yet significant variables have been continually utilised. A "variable" is understood to be a characteristic of the system that can be measured and that assumes different numerical values at
different times, (Freeze, 1974, p.634). The more important variables, those that continually appear in the literature, are listed in Table 2.1. Many of these variables have been defined in a slightly different manner even though they measure essentially the same aspect of the streamflow. For example, Appendix 1 lists a number of definitions for the hydrologic variable, 'lag time', which essentially measures the time elapsed between a precipitation event and its subsequent runoff event.

The extent to which urbanisation alters the hydrologic performance of a watershed is difficult to evaluate because runoff data are usually not available before the encroachment of urbanisation. This lack of data has resulted in two general methodologies:

a) The first involves the use of synthetic methods to simulate the hydrologic conditions of the watershed prior to urban development;

b) the second involves a direct comparison between existing urban and rural watersheds which are assumed to be hydrologically similar except for the effects of urbanisation, (Esprey, Winslow & Morgan, 1969, p.216).
FIGURE 2.1

DEFINITION OF HYDROGRAPH PROPERTIES

TIME

Tr = Time of Rise
Q = Peak Discharge
Q75 = 75% of the Peak Discharge value
Q50 = 50% of the Peak Discharge value
Tb = Time Base of the runoff hydrograph
W50 = Hydrograph width at Q50
W75 = Hydrograph width at Q75
Although the latter approach, which in essence depicts research of an empirical nature, appears to be the most predominant in research studies, both of them require the use of hydrologic variables for evaluating the effects of urbanisation. By far the most common procedure for evaluating these effects is to relate the hydrologic variables to some particular drainage basin characteristics. Consequently, the following sections discuss the changing relationships between certain variables and a number of measurable drainage basin factors, by presenting the findings of this research.

2.1.1 Time Distribution.

There are essentially two major hydrologic variables which can be considered separately herein; the lag time and the time of rise. The 'lag time' is generally described as the time elapsed between the precipitation event and it subsequent runoff hydrograph while the 'time of rise' is defined as the time between the beginning of the storm runoff and its peak discharge, see Figure 2.1.
2.1.1.1 Lag Time.

The most common method of measuring the effect of urbanisation on the time distribution of runoff has employed the variable, 'lag time'. Carter (1961) presented the first comprehensive study of lag time variations due to urbanisation. He defined the lag time as, "the average time interval (T4) between the centroids [4] of rainfall excess and of the resulting flood hydrograph," (p.10). In studying 20 basins in the area around Washington D.C., Carter suggested that the lag time approximated a function of the ratio: L/S^{0.5}. From the data provided by the undeveloped catchments, equation 2.1 was derived.

\[ T4 = 3.10 \left( \frac{L}{S^{0.5}} \right)^{0.6} \quad \text{(Eq. 2.1)} \]

where, \( L \) = total length of the main channel to of the rim the basin, (ml.)

\( S \) = the weighted slope of the main stream channel, (ft./ml.).

From Carter's findings summarised in Figure 2.2, it can be concluded that a partially sewered watershed [5] will reduce the lag time by approximately 60% and a completely sewered watershed will reduce the lag time by approximately 80%.

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EFFECT OF SUBURBAN DEVELOPMENT ON LAG TIME,
(after Carter, 1961)

Lag Time, T, in hours

L/S^0.5 L in miles, S in feet per mile

Figure 2.2

Legend:
- Natural Basins
- Partially Sewered Basins
- Completely Sewered Basins
FIGURE 2.3

EFFECT OF BASIN DEVELOPMENT ON LAG TIME,
(after Martens, 1968)

\[ T = 4.18 (L/S^{0.5})^{0.52} \quad \text{(Undeveloped Conditions)} \]
\[ T = 1.83 (L/S^{0.5})^{0.52} \quad \text{(Partly Developed Conditions)} \]
\[ T = (L/S^{0.5})^{0.52} \quad \text{(Urban Conditions)} \]
It should be noted that Curve 3 on Figure 2.2 is derived solely from data provided by Snyder (1958); those basins being described as completely sewered with no natural channels. Anderson, D.G. (1963) also confirmed the magnitude of these results in concluding that complete sewering of basins in Virginia reduced the lag time by as much as 85%.

Martens (1968) utilising equations from both Carter's and Anderson's work derived his own empirical coefficients for the lag time equation, see Figure 2.3. "These equations indicate that the lag time (T3) for a particular point on a stream may be reduced to less than one-fourth (75%) of its natural value as a basin becomes fully developed," (Martens, 1968, p.16).

Eagleson (1962) extended the Unit Hydrograph concept to urban conditions to illustrate variations in lag time. He used the definition of lag time presented by Linsley, Kohler, Paulus (1958), (T1), which was then related to a geometrical parameter of the watershed, similar to the parameter devised by Carter, see Eq. 2.2.
FIGURE 2.4

LAG TIME, $T$, vs. $L_{Lca}/S^{0.5}$ (modified from Eagleman, 1962)

- Mountain D.A.
- Foothill D.A.
- Valley D.A.
- Louisville South
- Urban D.A.

$T_1 = 0.18 \times \frac{L_{Lca}}{S^{0.5}}$
$T_2 = 0.28 \times \frac{L_{Lca}}{S^{0.5}}$

$L_{Lca}$ in miles, $S$ in feet per foot

LAG TIME T', in hours
\[ T_1 = \frac{L \cdot Lca}{S^{0.5}} \quad \text{(Eq. 2.2)} \]

where, \( T_1 \) = the time from the beginning of the rainfall to the centroid of runoff;

\( L \) and \( S \) defined the same as Carter's;

\( Lca \) = the distance in feet measured along the main drainage channel from the point of interest to a point opposite the computed centroid of the drainage area.

From this equation Eagleson derived the empirical relation, shown in Eq. 2.3 and on Figure 2.4.

\[ T_1 = 0.18 w^{0.38} \quad \text{(Eq. 2.3)} \]

where, \( w \) = the right-hand side of Eq. 2.2.

From five urban watersheds in Louisville, Kentucky, Eagleson concluded that urbanisation caused reductions in lag time of 86%, 78%, and 49% when compared to the lag times of mountainous, foothill, and valley watersheds respectively, see Figure 2.4. However, Eagleson also applied another lag time definition, that listed as \( T_2 \) in Appendix 1, which rendered the empirical relation:

\[ T_2 = 0.06 w^{0.38} \quad \text{(Eq. 2.4)} \]

where, \( w \) = the right-hand side of Eq. 2.2.

This is also shown on Figure 2.4 as the dotted line and consequently shows that the definitions \( T_1 \) and \( T_2 \) produces a greater difference than those produced by the different land-uses.
Finally, Taylor (1975) compared the lag times between a rural subcatchment and its urban partner on the fringe of an urban area by averaging the hydrologic characteristics from 11 rainstorm events. The small instrumented catchment, containing an upper rural and a lower urban subbasin, was situated on the periphery of Peterborough, Ontario. The results indicated an implied reduction of the urban lag time to 46% of the average rural value.

2.1.1.2 Time of Rise.

This time distribution variable is associated with the hydrologic response to precipitation only, being the time from the beginning of the storm runoff to the peak discharge of that runoff event, see Figure 2.1. Van Sickle (1969) showed that in comparing the previous rural conditions to the urban conditions that the time to rise had decreased from 12 hours to 3 hours for the Brays Bayou catchment in Texas, see Table 2.2.

Similarly, Hollis (1974) in a study on the Canon's Brook, Essex, England showed that as the watershed experienced the progressive encroachment of urban land-use the time of rise of the average unit hydrograph for separate time periods decreased from 4.8 hours to 2.1 hours, a 55% reduction.
TABLE 2.2
UNIT HYDROGRAPH CHARACTERISTICS, BRAYS BAYOU TEXAS,

<table>
<thead>
<tr>
<th>Storm</th>
<th>Peak Discharge Rate, cfs.</th>
<th>Time to Peak, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>July, 1939</td>
<td>1,800</td>
<td>12</td>
</tr>
<tr>
<td>November, 1940</td>
<td>1,680</td>
<td>12</td>
</tr>
<tr>
<td>September, 1941</td>
<td>1,340</td>
<td>12</td>
</tr>
<tr>
<td>November, 1943</td>
<td>1,220</td>
<td>15</td>
</tr>
<tr>
<td>October, 1949</td>
<td>1,100</td>
<td>12</td>
</tr>
<tr>
<td>Synthetic for U.S.C.E. design</td>
<td>1,800</td>
<td>12</td>
</tr>
<tr>
<td>May, 1953</td>
<td>2,200</td>
<td>6</td>
</tr>
<tr>
<td>April, 1959</td>
<td>4,640</td>
<td>4</td>
</tr>
<tr>
<td>October, 1959</td>
<td>4,200</td>
<td>5</td>
</tr>
<tr>
<td>June, 1960</td>
<td>4,560</td>
<td>3</td>
</tr>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate</td>
<td>6,000</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Thus, in conclusion it appears that the time distribution variables are reduced significantly by the effects of urbanisation.

2.1.2 Peak Discharge.

There are two main analyses used to measure the effect of urbanisation on peak discharge; flood frequency analysis and hydrograph analysis. Under hydrograph analysis, which concentrates on discrete precipitation - runoff events, only the hydrograph peaks (Q on Figure 2.1) are considered. Under flood frequency analysis, which uses probability theory to relate the size of a flood to a probability of occurrence,
the mean annual flood is considered separately from the more extreme but lower frequency floods.

2.1.2.1 Hydrograph Peak.

In analysing a total of 21 rainstorm events, Taylor (1975) found that urban peaks flows always exceeded rural values by at least a factor of two. For 10 events that occurred during the fall the average urban hydrograph peak exceeded that of the rural peak by 2.22 times. This ratio was not constant but varied presumably with the antecedent moisture conditions and individual storm characteristics. However, for 11 storm events recorded in the spring the ratios between urban and rural hydrograph peaks per unit area were highly variable, ranging from 3.0 to 17.8, with an average urban value 7.1 times the rural.

The Unit Hydrograph analysis has been commonly used to study these effects. Crippen (1965) constructed the average 15-minute unit hydrographs for Sharon Creek, California for a period before urban development and for a period after development. The unit hydrographs reflect the basin characteristics under the regime of the stream before and after the development. The average peak discharge was found to have increased from 180 cfs. to 250 cfs.
FIGURE 2.5

MEAN UNIT HYDROGRAPHS FOR THREE STAGES IN THE URBANISATION OF THE CANON'S BROOK CATCHMENT, (after Hollis, 1974, p.132)

FIGURE 2.6


<table>
<thead>
<tr>
<th>Discharge Type</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-12 JULY 1939</td>
<td></td>
</tr>
<tr>
<td>22-25 NOV 1940</td>
<td></td>
</tr>
<tr>
<td>23-25 SEPT 1941</td>
<td></td>
</tr>
<tr>
<td>12-19 MAY 1953</td>
<td></td>
</tr>
<tr>
<td>8-11 APRIL 1959</td>
<td></td>
</tr>
<tr>
<td>23-27 JUNE 1960</td>
<td></td>
</tr>
</tbody>
</table>
Hollis (1974) constructed the average one-hour unit hydrograph for three separate periods throughout which the encroachment of urban land-use continued, see Figure 2.5. The unit hydrograph for 1950-1954 exemplifies the "pre-urban" or "natural" conditions, while the remaining two periods are influenced by a progressive development such that by 1968 some 16.6% of the catchment was paved.

A similar catchment study can be found in the USA. Van Sickle (1969) analysed 27 years of records from the Brays Bayou, Houston, Texas. During this period the catchment changed from undeveloped farmland to an extensively urbanised area and the corresponding change in the unit hydrographs is illustrated in Figure 2.6 and Table 2.2. These above examples illustrate an exception to the rule that data is unavailable before urban development; that detrimental situation mentioned at the beginning of Section 2.1.

Because of the lack of hydrologic data in the years preceding urbanisation of the Waller Creek, Austin, Texas it was necessary to develop empirical equations describing the hydrograph under conditions before urbanisation. This was accomplished by analysing data from 11 rural watersheds from Southern USA, (Esprey, Morgan, & Masch, 1965). These equations described all the hydrologic variables indicated in Figure 2.1 in terms of certain basin characteristics. The
relationships were derived by applying a stepwise multiple linear regression analysis. The peak discharge derived for rural basins is shown by Eq. 2.5.

\[ QR = 1.70 \times 10^3 A^{0.88} (T_{RR}-0.30) \]  
(Eq. 2.5)

Where, \( QR \) = peak discharge for a rural catchment, (cfs.);
\( A \) = drainage area (sq.ml.);
\( T_{RR} \) = time of rise, see Figure 2.1, for a rural catchment, (min.);

Subscript \( R \) refers to rural conditions.

A similar regression analysis had already produced an empirical equation for the hydrologic variable, time of rise, See Eq. 2.6:

\[ T_{RR} = 1.24 \left( \frac{L}{S^{0.5}} \right)^{0.36} \]  
(Eq. 2.6)

\( L \) = total length of the main channel to the rim of the basin, (ml.);
\( S \) = the weighted slope of the main stream channel, (ft./ml.).

This relationship compares very closely with that of Carter (1961), see Eq. 2.1. It was found that the introduction of the time of rise, which represents the integrated effects of the geometric characteristics of the watershed, produced considerable improvement in the statistical fit of the peak discharge regression equation.

Using the above equations, together with similar equations derived for the remaining hydrograph variables,
the 30-minute unit hydrograph shape was constructed for the Waller Creek under assumed rural conditions. This hydrograph was compared to the existing 30-minute unit hydrograph to evaluate the effect of existing urbanisation on the hydrograph shape, (Esprey, Morgan, & Masch, 1966). Following a similar procedure empirical equations were derived from 22 urban watersheds so that the effect of future urban development could be assessed for the Waller Creek, by a comparison of the existing and the predicted hydrographs. The equation derived for the peak discharge of the urban catchments could best be expressed as a function of the drainage area and the time of rise; see Eq. 2.7.

\[ QU = 1.93 \times 10^4 A^{0.91} TrU^{-0.94} \]  
(Eq. 2.7)

where, \( QU \) = the peak discharge of an urban catchment, (cfs.);

\( A \) = area of catchment, (sq.m.);

\( TrU \) = time of rise of an urban catchment, (min);

Subscript U refers to urban catchments.

Again, the time of rise was empirically derived, See Eq. 2.8.
TrU = 20.8 \( L^{0.29} S^{-0.11} I^{-0.61} \) (Eq. 2.8)

where, \( I \) = the percentage of impervious cover,
\( L \) and \( S \) are previously defined,
\( \varnothing \) = a new urban factor to account for the reduction in the time of rise that is due to channel improvement by the addition of storm sewers.

Table 2.3 provides the classification.

**TABLE 2.3**

**THE \( \varnothing \) CLASSIFICATION,**

(from Esprey, Morgan, & Masch, 1965).

<table>
<thead>
<tr>
<th>( \varnothing )</th>
<th>CLASSIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>Extensive channel improvement and storm sewer system, closed conduit channel system.</td>
</tr>
<tr>
<td>0.8</td>
<td>Some channel improvement and storm sewers; mainly cleaning and enlargement of existing channel.</td>
</tr>
<tr>
<td>1.0</td>
<td>Natural channel conditions.</td>
</tr>
</tbody>
</table>

The derived equations were then applied to both the gauging stations on the Waller Creek, one at 23rd. and one at 38th. St., to establish hydrographs under rural, existing and predicted urban development in order to determine the present and future effects of urbanisation on the runoff characteristics of the watershed.
### TABLE 2.4
SUMMARY OF SOME EFFECTS OF PRESENT AND FUTURE URBAN DEVELOPMENT ON THE WALLER CREEK WATERSHED AT 23rd. ST.

<table>
<thead>
<tr>
<th>Stage of Development</th>
<th>Time of Rise (mins)</th>
<th>Percent Difference Based on Rural Values</th>
<th>Peak Discharge (cfs)</th>
<th>Percent Difference Based on Rural Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural I = 0%</td>
<td>105</td>
<td>0</td>
<td>1,460</td>
<td>0</td>
</tr>
<tr>
<td>Present I = 27%</td>
<td>57</td>
<td>-46%</td>
<td>2,200</td>
<td>+51%</td>
</tr>
<tr>
<td>Future I = 50%</td>
<td>50</td>
<td>-52%</td>
<td>2,360</td>
<td>+62%</td>
</tr>
</tbody>
</table>

### TABLE 2.5
SUMMARY OF SOME EFFECTS OF PRESENT AND FUTURE URBAN DEVELOPMENT ON THE WALLER CREEK WATERSHED AT 38th ST.

<table>
<thead>
<tr>
<th>Stage of Development</th>
<th>Time of Rise (mins)</th>
<th>Percent Difference Based on Rural Values</th>
<th>Peak Discharge (cfs)</th>
<th>Percent Difference Based on Rural Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural I = 0%</td>
<td>103</td>
<td>0</td>
<td>880</td>
<td>0</td>
</tr>
<tr>
<td>Present I = 21%</td>
<td>55</td>
<td>-47%</td>
<td>2,930</td>
<td>+6%</td>
</tr>
<tr>
<td>Future I = 50%</td>
<td>47</td>
<td>-54%</td>
<td>1,460</td>
<td>+66%</td>
</tr>
</tbody>
</table>

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A summary of the estimated changes in the time of rise and the peak discharge is presented in Table 2.4 and 2.5. (from Esprey, Morgan, & Masch, 1966, Tables 10 & 11).

This research was continued by Esprey, Winslow, & Morgan (1969) who derived new empirical equations which included 11 urban and 6 rural watersheds from Houston, Texas. The combined data represented a total of 33 urban and 17 rural watersheds. The analysis showed that channel roughness in the Houston catchments caused a significant variation. This variation was attributed to seasonal variations in channel vegetation. The effect of channel vegetation growth resulted in a diminished peak discharge, as illustrated by two 30-minute unit hydrographs for Berry Bayou, Houston, see Figure 2.7. To account for this difference the Ø value was redefined to reflect the changes in channel roughness as a result of seasonal variation in vegetation, see Table 2.6.

Using the new equations the Hunting Bayou at Houston indicated that the present peak discharge with conditions of 27% impervious cover and a Ø value of 1.25, had increased about 50% from its pre-urban value. In a confirmatory research project Brater and Sangal (1969) examined the equations of Esprey et al. (1966) for six watersheds in the Detroit area.
FIGURE 2.7

30-MINUTE UNIT HYDROGRAPHS (BERRY BAYOU AT GILPIN)
LIGHT AND HEAVY VEGETATION,
(from Esprey et al., 1969, p.224).
### TABLE 2.6

**REDEFINED Ø CLASSIFICATION**

(from Esprey, Winslow, & Morgan, 1969).

\[ \bar{\theta} = \theta_1 + \theta_2 \]

<table>
<thead>
<tr>
<th>( \theta_1 )</th>
<th>CLASSIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>Extensive Channel Improvement and Storm-sewer System, Closed Conduit Channel System</td>
</tr>
<tr>
<td>0.8</td>
<td>Some Channel Improvement and Storm Sewers; mainly Cleaning and Enlargement of Existing Channel</td>
</tr>
<tr>
<td>1.0</td>
<td>Natural Channel Conditions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \theta_2 )</th>
<th>CLASSIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>No Channel Vegetation</td>
</tr>
<tr>
<td>0.1</td>
<td>Light Channel Vegetation</td>
</tr>
<tr>
<td>0.2</td>
<td>Moderate Channel Vegetation</td>
</tr>
<tr>
<td>0.3</td>
<td>Heavy Channel Vegetation</td>
</tr>
</tbody>
</table>

They concluded that the peak values obtained have the same order of magnitude as those of the Detroit watersheds for both the urban and rural conditions, which provides some evidence as to the general applicability of these equations.

#### 2.1.2.2 Mean Annual Flood.

In a similar manner to the hydrograph analysis the influence of urbanisation on the mean annual flood has been evaluated in terms of the basin physiographic
characteristics. Carter (1961) related the mean annual flood to lag time, drainage area, and the percentage of impervious cover within the basin, as expressed in equations 2.9 and 2.10.

\[ Q = 223 K A^{0.85} T_4^{-0.45} \]  
(Eq. 2.9)

where, \( Q \) = mean annual flood, (cfs.);
\( A \) = drainage area, (sq.ml.)
\( T_4 \) = lag time as previously defined;
\( K \) = an adjustment based on the degree of impervious cover of the drainage area, such that:

\[ K = \frac{0.30 + 0.0045I}{0.30} \]  
(Eq. 2.10)

where, \( I \) = percentage of impervious cover within the drainage basin.

Eq. 2.9 was derived using a multiple regression analysis on data from 18 watersheds, which indicated a standard error of ±22 and ±29%. Then, using both Eqs. 2.7 and 2.10 in conjunction with Figure 2.2 the effect of urbanisation could be determined. For example, assume that the relation between \( T \) and \( L/S^{0.5} \) changes the values given in Curve 1 to the values given in Curve 2 on Figure 2.2 because of urban development, and that the percentage imperviousness is increased from 0 to 12%. Then the ratio of the mean annual flood under suburban conditions to that with undeveloped conditions can be calculated as follows:
Thus, the effect of suburban development in the basins around Washington D.C. is to increase the mean annual flood some 1.8 times its undeveloped value.

Martens (1968) continued this line of research in developing the equation for $K$, (Eq.2.10), as follows:

$$K = \frac{0.30 - 0.30(I/100) + 0.75(I/100)}{0.30} \quad (\text{Eq. 2.12})$$

$K$ = an adjustment based on the degree of impervious cover in the basin;

$I$ = the percentage of impervious cover within the basin.

The value 0.30 represents that proportion of any precipitation event that is converted into streamflow under natural conditions, while 0.75 represents the proportion of runoff expected from completely impervious basins. The figure 0.30 has been verified for streams around Charlotte, but the figure 0.75 has not yet been verified due to the lack of basins meeting the required specifications. Martens (1968, p.20) suggests that this figure is "reasonable". From this equation (Eq. 2.12) the mean annual flood is increased 2.5 times over the natural value for a basin with 100% impervious cover.

Using this revised equation (Eq. 2.12) Anderson, D.G. (1970) applied these concepts to 44 basins in North
Virginia, as compared to the 18 watersheds and 7 urban streams analysed by Carter and Martens respectively, and derived an equation which was extremely close to Carter’s original; compare Eqs. 2.9 and 2.13.

\[ Q = 230 K A^{0.82} T^{-0.48} \]  

(Eq. 2.13)

where all the variables are previously defined.

Researching along similar lines Wilson (1967), in analysing ten years of records from the city of Jackson, Mississippi, concluded that the mean annual flood increased by two to three times, compared the flood in adjacent rural areas which were analysed in an earlier study. The four basins analysed produced annual floods from just below 2 to 3.5 times their rural approximations, see Figure 2.8.

**EFFECT OF URBANISATION ON MEAN ANNUAL FLOODS IN JACKSON, MISSISSIPPI, (after Wilson, 1968).**

![Figure 2.8](image_url)
In concluding his research Wilson (1967) extrapolated his results to estimate the increase in flood size for a completely urbanised basin, with 100% impervious cover. He speculated that the annual flood could be increased approximately 4.5 times its rural value.

Anderson, D.G. (1970) continued this line of investigation by developing a ratio of the mean annual flood under certain hypothetical urban conditions to the mean annual flood under natural conditions. This ratio was calculated in terms of lag time (T), the impervious coefficient (K), the flood ratio (R), and the drainage area (A), as shown in Equations 2.14 and 2.15.

\[
\frac{Q_d}{Q_n} = \frac{230 K_d A^{0.82} T_d^{-0.48} R_d}{0.82 T_d^{-0.48}}
\]  \hspace{1cm} \text{(Eq. 2.14)}

\[
\frac{Q_d}{Q_n} = \frac{K_d R_d}{K_n R_n} \left(\frac{T_n}{T_d}\right)^{-0.48}
\]  \hspace{1cm} \text{(Eq. 2.15)}

where the subscripts [d] and [n] refer to the developed and natural conditions respectively and Q, T, K, A, are all previously defined. R is the flood ratio based upon interpolation between the ratios for the natural flow conditions and those for 100% impervious conditions derived from rainfall frequencies.

From this equation Anderson, D.G. computed a series of flood ratios for a number of predetermined urban conditions, see Table 2.7.
### TABLE 2.7


<table>
<thead>
<tr>
<th>Recurrence Interval (years)</th>
<th>Imperviousness (percent)</th>
<th>Developed to Undeveloped Ratio</th>
<th>Completely sewered basin</th>
<th>Basin having sewered tributaries, unaligned and specified (L/S&lt;sup&gt;0.5&lt;/sup&gt;)</th>
<th>Main channels, and specified (L/S&lt;sup&gt;0.5&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.1 1.0 10</td>
<td>0.1 1.0 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.33</td>
<td>0</td>
<td>3.07 2.76 2.44</td>
<td>2.40 2.20 2.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3.99 3.59 3.17</td>
<td>3.11 2.86 2.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5.37 4.83 4.27</td>
<td>4.20 3.85 3.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>7.68 6.90 6.10</td>
<td>6.00 5.50 5.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First of all, the urban conditions are based upon the extent of sewering; there being two divisions:

a) A completely sewered basin with aligned channels;

b) basins with sewered tributaries and unaligned channels.

Secondly, three different time travel factors or length-slope ratios are considered:

a) 0.1 represents a small, steep basin;

b) 1.0 represents an "intermediate" basin;

c) 10 represents a large, flat basin.

(The length-slope ratio is derived from $L/S^{0.5}$ so if (L) is small and (S) is large, as expected in a small, steep basin the resultant ratio would be low, around 0.1. Conversely, with (L) large and (S) small, as is possible in a large, flat basin, the resultant ratio would be large and represented by 10.0). So, if a basin which was intermediate in class, was completely sewered and had a 50% impervious cover Table 2.7 indicates that it would have a mean annual flood of 4.83 times its former natural value.

To conclude this section Hammer (1973) investigated the increase in mean annual floods from eight urbanising basins around Washington D.C. He used population density as an index of urbanisation because it could be easily estimated from Census Tract data and because the physical measurements of impervious areas were much more costly and time-consuming.
consuming, (p.13). His results indicated that the average annual flood increases by about 18% of its pre-urbanisation value for each 1000-person increase in residential population per square mile of watershed area. Thus, an increase in population density of 5500-6000 persons per square mile from the rural condition causes the average annual flood to double.

2.1.2.3 Low Frequency Floods.

In considering the effect of urbanisation in terms of flood frequencies less than the mean annual flood Hammer (1973) stated that,

"there is good reason to believe that urbanisation typically has less impact on the magnitude of low frequencies floods than is the case for high frequency floods," (p.37).

This belief is taken a stage further by Wilson (1967) who showed that the 50-year flood is only about twice the magnitude of the mean annual flood, a phenomena that differs considerably from that for rural areas where the 50-year flood is about three times the mean annual flood. The difference is attributed to storm sewers, gutters and man-made ditches which function well during high frequency floods but are overtaxed during extreme floods and hinder the rapid removal of runoff.

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However, opinions appear to differ with regard to how much the relative importance of urbanisation varies with the frequency of flood considered. Some researchers, especially those concentrating on basin lag time, tend to conclude that the increase in discharge due to urbanisation is substantial even for the 50-year flood even though the relative effect decreases. While many planners and engineers appear to assume that the effects on the 50-year and 100-year floods are rather negligible.

Moreover, the major difficulty encountered in attempting to relate urbanisation to floods which occur infrequently is the extreme shortage of streamflow data from urban basins. Furthermore, the evaluation of the flood frequency characteristics of an urban basin is complicated by the constantly changing urban landscape conditions. These limitations have to be borne in mind when considering, for example, the evaluation of the effect of urbanisation on floods of various frequencies produced by Martens (1968) and illustrated in Figure 2.9.

The ratio of various flood frequency sizes to the mean annual flood for a number of "natural" basins around the Charlotte area was calculated using procedures developed by Dalrymple (1960). These values were plotted on the left hand side of the graph, see Figure 2.9.

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FIGURE 2.9

A GRAPH SHOWING VARIATION OF FLOOD - FREQUENCY RATIO WITH PERCENT OF IMPERVIOUS AREA,
(after Martens, 1968).

RATIO TO MEAN ANNUAL FLOOD (R)

50 yr.
30 yr.
25 yr.
20 yr.
15 yr.
10 yr.

2.33 yr.

0 20 40 60 80 100

IMPEVIOUS AREA IN PERCENT

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Theoretical ratios were established for completely urbanised basins by converting ratios of rainfall intensities of a given frequency into ratios of runoff values of the same frequency, since runoff from a completely impervious basin will be directly proportional to the precipitation falling upon it. Then the factor $K$ was taken into consideration by applying Eq. 2.12. Finally, these ratios were plotted on the right hand side of the graph on Figure 2.9 and the corresponding frequencies were joined by straight lines. From this graph, the mean annual flood can conceivably increase 2.5 times over its natural value for a basin with 100% impervious cover. The value of the 50-year flood, however, hardly increases with a change from natural conditions to complete imperviousness. Thus the graph depicts a decreasing degree of effect with an increasing flood magnitude. Hammer (1973) quotes similar results, but considers the influence of urbanisation to be greater than that suggested by Martens (1968),

"although the effect of urbanisation on peak discharge decreases with recurrence interval in relative terms, it generally does not decrease in absolute terms; thus the effect must be considered substantial for all recurrence intervals up to 100 years, (p.67)."

In this case Hammer (1973) used an urbanisation index which represented the expected channel enlargement ratio due to urbanisation: the channel cross-section area after
urbanisation, divided by channel cross-section before urbanisation. This ratio (R) had already been developed in an earlier study, Hammer (1972), and was re-applied to 53 streams in New Jersey, Pennsylvania, Maryland, and Delaware. Figure 2.10 illustrates the relative increase in floods of various frequencies which result from urbanisation, based on the results from Hammer's research. The channel enlargement ratio can refer either to the predicted ratio of channel enlargement, based on land-use measurements or to a ratio based on observed channel areas. These results are however, incompatible in terms of a direct comparison with the results from Martens' research because of the two different urbanisation indices employed in their respective studies.

Hollis & Luckett (1976) applied the techniques devised by Hammer to identify the morphometric and land-use factors that affected channel size in a wide range of catchments in West Sussex, England [6]. They concluded that,

"Some support can be given to the idea that natural river channels are enlarged by increased flood flows from new urban areas constructed in their catchments. However, the evidence is somewhat equivocal. In the West Sussex study the levels of statistical explanation were rather low," (p.362).

The indecisive results obtained from this study were discussed in an enlightening critique by Park (1977) who presented a number of feasible explanations for these 'surprisingly' indecisive results.
FIGURE 2.10

TABLE 2.8
FLOOD-PEAK-MAGNITUDE RATIOS FOR DEVELOPED BASINS TO NATURAL BASINS, (after Anderson, D.G. 1970)

<table>
<thead>
<tr>
<th>Recurrence Interval (years)</th>
<th>Imperviousness (percent)</th>
<th>Developed to Undeveloped Ratio</th>
<th>Developed to Undeveloped Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Completely sewered basin</td>
<td>I Basin having sewered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>having aligned channels</td>
<td>I tributaries, unaligned</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and specified (L/S0.5)</td>
<td>I main channels, and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>I specified (L/S0.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>3.07</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3.27</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.64</td>
<td>3.28</td>
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<tr>
<td></td>
<td>100</td>
<td>4.12</td>
<td>3.70</td>
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<td>50</td>
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<td>3.07</td>
<td>2.76</td>
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<td>3.30</td>
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<td>2.76</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>3.07</td>
<td>2.76</td>
</tr>
</tbody>
</table>
Anderson, D.G. (1970) developed Eq. 2.15 and Table 2.7 to account for the sizes of different flood frequencies, see Table 2.8. This table supports the general conclusions that:

1) A completely impervious surface increases the average size flood by a factor of 2.5, but impervious surfaces have a decreasing effect upon larger floods and so an insignificant effect upon the 100-year flood.

2) The effect of sewer installation, independent of impervious development, is to increase flood peak magnitudes by a factor of 2 to 3.

In an extensive study by Esprey & Winslow (1974) this research was continued by comparing the "dimensionless" flood frequency of rural and urban watersheds. The "dimensionless" flood frequency is defined as the peakflow discharge (Q) for a specific frequency of occurrence, divided by the mean annual flow (Q2.33). A graph was plotted of this ratio for the familiar Waller Creek, as urban watersheds, and of the nearby Wilbarger Creek to represent a rural watershed. The results are shown in Figure 2.11, which also indicates the actual discharge values.

To compare the urban and rural conditions directly, the peak flows were reduced to a unit area.
THE "DIMENSIONLESS" FLOOD FREQUENCY CURVES FOR THE WILBARGER CREEK AND THE WALLER CREEK
(from Esprey & Winslow, 1974).

FIGURE 2.11

(Q/A) OF WALLER CREEK/(Q/A) OF WILBARGER CREEK VERSUS RECURRENCE INTERVAL

FIGURE 2.12
FIGURE 2.13

THE FLOOD FREQUENCY CURVES OF TWO HOUSTON CATCHMENTS.

The Curves for Brays Bayou at Houston, Texas.

The Curves for Whiteoak Bayou at Houston, Texas.

<table>
<thead>
<tr>
<th>DEVELOPED FLOW (D)</th>
<th>UNDEVELOPED FLOW (UD)</th>
<th>QD / QUD</th>
</tr>
</thead>
</table>

Developed Flow (D) - Dotted line
Undeveloped Flow (UD) - Dashed line
QD / QUD - Solid line

Recurrence Interval, in Years.

Discharge (CFS)
The data were analysed for a given recurrence interval in terms of the ratio of the flow per sq.ml. of the basin (Q/A) for Waller Creek, to the flow per sq.ml. of the basin for Wilbarger Creek. Figure 2.12 shows the resultant graph in which the effect of urbanisation appears to increase up to a recurrence interval of 5 years after which the effect declines. Esprey & Winslow (1974) suggest that the peak between 2 and 5 years is probably a reflection of the design frequency of the storm sewer system for Waller Creek.

However, the Brays Bayou and Whiteoak Bayou in Houston shows no decreasing effect with increasing recurrence interval, see Figure 2.13(a) and (b) respectively. In order to attempt to account for these differences a larger sample of watersheds was studied. First of all, the flood frequency curves were generated for 27 Texas catchments to calculate the flood peaks at the 2.33-, 5-, 10-, 20-, and 50-year recurrence intervals. Then these values were related to physiographic, rainfall, and urban factors for each flood frequency. The resultant equations are listed in Table 2.9. The correlation coefficients were estimated on the logarithms of the data whereas the average absolute percentage errors were based on the actual flow data. It should be noted that the channel urbanisation factor $\theta$ becomes more significant and the percentage of impervious cover less significant as the recurrence interval increases.
### TABLE 2.9

**Derived Flood Frequency Equations for 27 Texas Watersheds, (from Esprey & Winslow, 1974).**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Correlation Coefficient</th>
<th>Av. Absolute Error, as a Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 116 A 0.75 I 0.28 Ø -1.09</td>
<td>0.93</td>
<td>34</td>
</tr>
<tr>
<td>Q = 159 A 0.77 I 0.27 Ø -1.23</td>
<td>0.92</td>
<td>36</td>
</tr>
<tr>
<td>Q = 193 A 0.78 I 0.27 Ø -1.40</td>
<td>0.92</td>
<td>39</td>
</tr>
<tr>
<td>Q = 226 A 0.79 I 0.27 Ø -1.58</td>
<td>0.91</td>
<td>42</td>
</tr>
<tr>
<td>Q = 268 A 0.79 I 0.26 Ø -1.83</td>
<td>0.90</td>
<td>47</td>
</tr>
</tbody>
</table>

### TABLE 2.10

**Derived Flood Frequency Equations for All 60 Urban Watersheds, (from Esprey & Winslow, 1974).**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Correlation Coefficient</th>
<th>Av. Absolute Error, as a Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 169 A 0.77 I 0.42 Ø 0.42 R 1.80 Ø -1.17</td>
<td>0.97</td>
<td>30</td>
</tr>
<tr>
<td>Q = 172 A 0.80 I 0.27 Ø 0.43 R 5 Ø -1.21</td>
<td>0.97</td>
<td>31</td>
</tr>
<tr>
<td>Q = 178 A 0.82 I 0.26 Ø 0.44 R 10 Ø -1.32</td>
<td>0.96</td>
<td>31</td>
</tr>
<tr>
<td>Q = 243 A 0.84 I 0.24 Ø 0.48 R 20 Ø -1.38</td>
<td>0.96</td>
<td>32</td>
</tr>
<tr>
<td>Q = 297 A 0.85 I 0.22 Ø 0.50 R 50 Ø -1.61</td>
<td>0.96</td>
<td>34</td>
</tr>
</tbody>
</table>
**TABLE 2.11**

**FLOOD DISCHARGE, PREDICTED VERSUS MEASURED**

FOR BRAYS BAYOU AT HOUSTON, TEXAS.

<table>
<thead>
<tr>
<th>Flood</th>
<th>Measured in cfs. (cumecs)</th>
<th>Predicted in cfs. (cumecs)</th>
<th>Error, as a Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2.33</td>
<td>6,810 (191)</td>
<td>8,700 (244)</td>
<td>+28</td>
</tr>
<tr>
<td>Q 5</td>
<td>10,400 (291)</td>
<td>13,000 (364)</td>
<td>+25</td>
</tr>
<tr>
<td>Q 10</td>
<td>13,110 (367)</td>
<td>17,400 (487)</td>
<td>+33</td>
</tr>
<tr>
<td>Q 20</td>
<td>15,460 (433)</td>
<td>20,500 (575)</td>
<td>+33</td>
</tr>
<tr>
<td>Q 50</td>
<td>18,080 (505)</td>
<td>25,400 (711)</td>
<td>+40</td>
</tr>
</tbody>
</table>

**TABLE 2.12**

**FLOOD DISCHARGE, PREDICTED VERSUS MEASURED**

FOR PIMMIT RUN AT ARLINGTON, VIRGINIA.

<table>
<thead>
<tr>
<th>Flood</th>
<th>Measured in cfs. (cumecs)</th>
<th>Predicted in cfs. (cumecs)</th>
<th>Error, as a Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q 2.33</td>
<td>1,470 (41)</td>
<td>1,320 (37)</td>
<td>-10</td>
</tr>
<tr>
<td>Q 5</td>
<td>2,160 (60)</td>
<td>1,880 (53)</td>
<td>-13</td>
</tr>
<tr>
<td>Q 10</td>
<td>2,780 (78)</td>
<td>2,520 (71)</td>
<td>-9</td>
</tr>
<tr>
<td>Q 20</td>
<td>3,410 (95)</td>
<td>2,980 (83)</td>
<td>-13</td>
</tr>
<tr>
<td>Q 50</td>
<td>4,290 (120)</td>
<td>3,780 (106)</td>
<td>-12</td>
</tr>
</tbody>
</table>

(cumecs) - cubic metres per second, see [14].

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The same procedure was then carried out on 26 East coast catchments and it was found that the slope of the channel \( S \) was significant while the \( I \) and \( \theta \) factors were insignificant. Finally, a total of 60 catchments throughout USA were processed and it was concluded that the total rainfall for a given duration \( R \) became an important variable; the equations are listed in Table 2.10.

To test these equations two urban catchments that had not been used in the derivations were studied. The equations were used to predict the flood peaks at various frequencies. These predicted values were then compared to the measured values from the catchments. It was found that the equations consistently predicted values that were approximately 30% too high for the Brays Bayou catchment in Texas, see Table 2.11. However, the predicted values fared much better for the Pimmit Run catchment in Virginia, in that they recorded values consistently below the measured with an average error of only 12%, see Table 2.12.

In conclusion, the majority of research suggests that the effect of urbanisation on low frequency floods decline relatively as the frequency decreases. However, there is still an increase in absolute terms. Some researchers suggest that for the most extreme floods, for example, the 100-year flood, the effect of urbanisation is negligible, whereas others indicate that the effect is still significant.
2.1.3 Total Runoff Yield.

Wiitala (1961) noted that the difference in peak flow was due entirely to the shape of the hydrograph and that there was no difference in the volume of surface runoff. However, there is substantial research evidence to suggest the contrary.

For example, Harris & Rantz (1964) observed a large increase in the volume of storm runoff as a result of urban development in the 5.1 sq.ml. basin of Permanente Creek, in California. In 1945 only 4% of this area was covered by impervious surfaces and the volume of local storm discharge was less than the seepage capacity of the channels, so that the recharge of the underlying groundwater body occurred readily. The streamflow entering the study area was greater than that leaving the area. If the total outflow from the study area is considered to be the sum of the streamflow leaving the area, and the channel seepage within the area, the ratio of the total outflow to the streamflow entering was 1.18. Substantial urban development occurred during the period 1951-1955, and by 1958 the degree of imperviousness had increased to 19%. Harris & Rantz used a double mass curve analysis on the annual streamflow record to show that by 1958 the storm discharge had increased, being far in
excess of the channel losses, and that the ratio of total outflow to inflow had increased to 1.70. This indicated an almost fourfold increase in the local storm discharge since 1945.

As part of their study, Esprey, Morgan, & Masch (1966) also considered runoff yield. In an analysis of unit storm data, 24 separate storms indicated that,

"as impervious cover continues to increase, the runoff yield from all stations on the Waller Creek basin will continue to increase," (p.85).

In order to evaluate this increase, a rainfall-runoff relation was derived with impervious cover as one of the assumed independent variables, along with the antecedent precipitation index, and the amount and duration of rainfall. In the following equation 2.16 impervious cover was introduced in the form (I+1) in order to determine the runoff from a storm under conditions of zero impervious cover,

\[
R = \frac{(I + 1)^{0.339} (WMR)^{1.72} (API)^{0.0741}}{0.0973} \frac{1}{Dt}
\]  

(Eq. 2.16)

where,  
\begin{align*}
R &= \text{runoff yield (in./ml.);} \\
I &= \text{percentage of impervious cover;} \\
WMR &= \text{amount of rainfall, (ins.);} \\
API &= \text{antecedent precipitation index;} \\
Dt &= \text{duration of rainfall, (min.).}
\end{align*}
From this equation the increase in runoff from an increasing impervious cover can be determined by evaluating the \((I+1)\) factor, as compared to that produced by conditions of zero impervious cover. The percentage increase in runoff based on rural conditions is presented in Figure 2.14.

**FIGURE 2.14**

PERCENT INCREASE IN UNIT YIELD AS A FUNCTION OF IMPERVIOUS COVER (23rd. St.), (from Esprey, Morgan, & Masch, 1966).
Lastly, James (1965) used the Stanford Watershed Model to develop a synthetic continuous long term hydrograph for Morrison Creek, Sacramento Co., California, covering the years 1905-1963. The water balance parameters required to calibrate the model were derived to represent rural conditions, or those before urban development. The comparison of the synthetic and recorded hydrographs consequently attempted to illuminate the progressive urban development into the catchment in terms of the changing hydrologic response. James (1965, p.232) concluded that the effects of complete urbanisation over a 10 year period resulted in a runoff yield some 2.29 times the previous rural value. Streamflow was increased in varying amounts, as much as six times the rural value in the wettest year and greater than 125 times in the driest year. The effects shown in the hydrographic response demonstrated the reduced role of soil moisture storage in urban areas, the increase in off-season and lesser floods, and a decline in the baseflows.

2.1.4 A Synthesis.

To conclude the section on the "Changes in Streamflow Components" a brief outline and discussion of a paper by Leopold (1969) is presented. It attempted to summarise
existing knowledge on the effects of urbanisation on hydrologic factors. Leopold notes that there are four interrelated but separable effects of land-use changes on the hydrology of an area:

1) Changes in the peak flow characteristics;
2) changes in the total runoff;
3) changes in the quality of water;
4) changes in the hydrologic amenities.

Only the former two have been considered in the previous sections, and these can be viewed together as the runoff or flow regimen.

In order to summarise the effects of urbanisation the principal factors affecting runoff, impervious areas and the amount of sewer installation as a percentage of the total drainage area, were plotted against one another and connected by isopleths which illustrated the ratio of peak discharge under different urban conditions to the peak discharge under natural conditions, see Figure 2.15. This graph used the results of most of the studies mentioned previously, having first reduced them to a unit area of one square mile. Thus if urbanisation of a square mile catchment resulted in 60% of the area being rendered impervious and 40% being served by sewers the net effect on the peak discharge would be to increase its value approximately three times over its former rural value.
FIGURE 2.15
EFFECT OF URBANISATION ON MEAN ANNUAL FLOOD
FOR A ONE-SQUARE MILE DRAINAGE AREA,
(from Leopold, 1969).

FIGURE 2.16
FLOOD-FREQUENCY CURVES FOR A ONE-SQUARE MILE BASIN
IN VARIOUS STATES OF URBANISATION, (from Leopold, 1969).
A second method of summarising these effects related the degree of urbanisation to the size of flood of a given frequency. This is graphically expressed in Figure 2.16. The graph shows the curves converging at the low flow values. Leopold explains this convergence by the fact that the most frequent flows are increased by smaller ratios than the mean annual flood. Also these flows are not sustained by groundwater as in a natural basin. Leopold (1969) stated that, "Obviously the frequency curves are extrapolations based on minimal data and require collaboration or revision as additional field data becomes available," (p.10). Some research tends to dispute Leopold's results and his explanation of Figure 2.16.

Crippen & Waananen (1969) found that the Sharon Creek, near San Francisco changed after urban development from an ephemeral stream with a flow on only 20 days per annum into a perennial stream. A similar change was noted by Harris & Rantz (1964). Hollis (1975) also noted that as a result of paving 16.6% of a catchment the modal flow [7] was increased from 2 cfs. to 5 cfs. and the frequency of floods in the range of 40 cfs. to 100 cfs. had increased from 8 to 27 per annum. Hollis reasoned that the paved surfaces produced runoff and thus a rise in streamflow from very modest rainstorms which under natural conditions would be entirely absorbed by soil storage.
Using a much larger data base, Hollis (1975) attempted to revise Leopold's synthesis. He expressed the ratio of peak discharge after urbanisation to that before urbanisation as a function of the percentage of the catchment paved and to the return period of the flood, see Figure 2.17. However, in this case the effect of urbanisation has again been reduced to a single factor, which is considered as unrealistic. Hollis (1975) does, however, note that the position of urban development in the catchment and the degree of improvement of the drainage network have both been shown to be particularly important additional measures of urbanisation. Furthermore, Figure
2.17 allows the lower frequency floods to be considered. Justification of this consideration is expressed in that these more extreme floods can cause the most significant damage. The initial graph by Leopold, Figure 2.15, deals only with the mean annual flood while the subsequent graph, Figure 2.17 only speculates up to the 10-year flood.

In spite of the reservations Figure 2.16 suggests that:

1) floods with a return period of one year or more are not appreciably affected by a 5% paving of their catchment area;

2) small floods may be increased by a factor of 10 or more depending upon the degree of urbanisation;

3) floods with a return period of 100 years may be doubled in size by the complete urbanisation of a catchment provided that at least 30% of the basin is rendered impervious;

4) the effect of urbanisation declines in relative terms as flood recurrence intervals increase, (Hollis, 1975, p.434). In conclusion, the effect of urbanisation can still be shown in some cases to be significant even for the 100-year flood, but the extent of the effect is in some dispute, varying from a doubling in size to insignificant.

Summarising this section (2.1) in qualitative terms the effects of urbanisation shorten the time distribution variables; increases the peak discharges of the flows, the
amount depending upon the return period or the flood magnitude; and finally increases the volume of runoff, due to the increase in smaller floods even though the contribution of groundwater decreases. All these effects are dependent upon the degree and type of urbanisation imposed on the catchments. The manner by which urbanisation actually affects the runoff and those components of the urban landscape that contribute to these effects are now discussed in the following section.
2.2 The Manner in which Urbanisation causes Changes in Streamflow.

The ways in which urbanisation affect streamflow has until now been discussed in terms of the changes in the streamflow itself; for example the increase in peak discharge. How the actual changes in the streamflow have arisen and which components of the urban landscape actively contribute to producing these changes will now be considered. Then, some of the methods by which urban components have been actually measured or quantified will be reviewed.

The changes expressed in streamflow variables illustrate the interference by urbanisation in the natural drainage process. Figure 2.18 is described as the "pre-urban hydrological system" and illustrates the water components for a typically large sector of the land prior to its urbanisation. The complexities imposed on this system by urbanisation can be appreciated by comparing Figure 2.18 with Figure 2.19, a simplified "urban hydrologic system", (UNESCO, 1974). The streamflow component, only part of the complete hydrologic cycle, is marked on both figures by a thickened continuous line and indicates the numerous paths and processes introduced by urbanisation and which contribute to the streamflow components.
FIGURE 2.18

PRE-URBAN HYDROLOGIC SYSTEM,
(from UNESCO, 1974, p.17).

Subject to modification by Agrarian Activity

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URBAN HYDROLOGIC SYSTEM, (from UNESCO, 1974, p.18).
Essentially there are two phases in which the streamflow is altered:

(a) the infiltration possibilities are reduced when the natural ground surface is replaced by impervious surfaces, such as highways, streets, parking lots, roofs, and buildings; all features common to the urban landscape. This phase particularly alters the volume of the streamflow. The infiltration of the pervious or urban green areas can also be affected, by bulldozing, soil mixing, and other technical procedures involved in construction of a city.

(b) the drainage efficiency within urban areas is increased dramatically by the introduction of a dense network of artificial drains, (Lindh, 1972). These tributary drains remove the runoff much more rapidly than natural channels thus compressing the time of travel to the main channels and consequently playing a major role in determining the shape of the hydrograph.

It would be difficult to place one phase above the other in importance, yet the great majority of recent investigations have been devoted to a better understanding of those factors affecting the shape of the hydrograph (essentially the second phase) while giving only cursory attention to the factors which determine the total volume of streamflow. These two phases are considered below as the infiltration characteristics (first phase) and drainage channel characteristics (second phase).
2.2.1 Infiltration Characteristics.

The actual losses that occur to different storages on urban watersheds are no different from those that occur on natural watersheds. Basically, they include interception, depression storage, and infiltration, (Viessman, 1966, p.407). However, the relative importance and the actual volumes of these losses are drastically altered for impervious areas and slightly altered for pervious areas within urban areas. For impervious areas the primary loss is depression storage, while interception and infiltration, especially for modelling purposes, can be considered as virtually non-existant. Depression storage is described by McPherson, (1974):

"Some of the precipitation which reaches roofs, pavements and other impervious surfaces is trapped in the many shallow depressions of varying size and depth present on practically all urban surfaces. There have been no field measurements of depression storage because of the obvious difficulties in obtaining meaningful data," (p.154).

There appears to be some research evidence which contradicts the above statement about the field data on depression storage. Viessman (1966) measured the losses attributed to depression storage from four very small urban watershed plots, all with 100% imperviousness, and ranging in size from 0.4 to 1 acre. The average losses for each
plot, which were suggested above as being almost entirely composed of depression storage, were calculated and are presented with other plot information in Table 2.13.

<table>
<thead>
<tr>
<th>Location</th>
<th>Plot Id No.</th>
<th>Area (acres)</th>
<th>Average losses per storm (ins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore</td>
<td>SPL 1</td>
<td>0.395</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>SPL 2</td>
<td>0.469</td>
<td>0.06</td>
</tr>
<tr>
<td>Newark</td>
<td>N 9</td>
<td>0.636</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>N 12</td>
<td>0.955</td>
<td>0.14</td>
</tr>
</tbody>
</table>

These average losses compare favourably with those suggested by Tholin & Keifer (1960), who recommended a retention or depression storage value of 1/16th. (0.0625) of an inch for pavements.

Bridge & Kakela (1975) used these empirically derived results to assess the value of the initial volume of storage used in a model for estimating water surplus, evaporation, and deficit of impervious areas. They used 0.067 inches as the mean value for Viessman's three most reliable measurements to determine the initial loss of precipitation from impervious runoff.

Brater (1968) suggested that values of this magnitude could be inconsequential when dealing with large precipitation - runoff events. Conversely one could assume
that this storage has a recognisable effect on small rainstorms. Viessman & Miller (1972) derived an empirical equation to estimate the runoff volume from rainfall on typical urban watersheds. These watersheds were not entirely impervious. For rainfall of less than 1.5 inches the runoff was estimated by the relationship between the percentage of impervious area and the percentage of excess rainfall, as shown in Eq. 2.17:

\[ R = 1.165(I - 0.17)(P - Ia) \]  
(Eq. 2.17)

where, 
\[ R = \text{runoff in inches}; \]
\[ I = \text{percentage of impervious area}; \]
\[ P = \text{rainfall in inches}; \]
\[ Ia = \text{initial abstraction in inches}. \]

The initial abstraction (Ia) was measured for the combined influence of the pervious and impervious areas. For example, Brater (1968) calculated the separate abstractions or retentions for the Red Run urban watershed near Detroit using Eq. 2.18 and 0.2 inches as the measured value of R.
RA = RiAi + RpAp \quad (\text{Eq. 2.18})

where,

- $R$ = the total initial retention for the watershed;
- $A$ = the total area of the basin;
- $Ai$ = the area of the impervious portion of the basin;
- $Ap$ = the area of the pervious portion of the basin;
- $Ri$ = the retention from the impervious portion;
- $Rp$ = the retention from the pervious portion.

Viessman, Keating, & Srinwasa (1970) suggested that an initial abstraction value ($Ia$) of 0.15 inches was reasonable, judging from previous work by Viessman, (1968) and from the measured value above provided by Brater (1968). Brater assuming an $Ri$ value of 0.05 inches and with an impervious area of 10%, calculated the retention of the pervious area as 0.217 inches; more than a fourfold increase over the impervious retention. However, the Red Run watershed had a relatively small extent of imperviousness. Miller & Viessman (1972) working with watersheds of much greater imperviousness found that the initial abstraction, $Ia$, should be much lower, being between 0.10 and 0.15 inches. Consequently they suggest Eq. 2.18 should be limited to urban watersheds with 35-80% imperviousness and for rainfall events of less than two inches.
This indicates that impervious areas can produce runoff from rainstorms which would otherwise be totally absorbed by the larger storage capacities of the pervious areas. Through the above discussion, "the opinion often expressed mainly by practising engineers that impervious areas produce a hundred percent runoff," (Lindh, 1972, p.190), has been disproved along with the notion that field measurements of depression storage are non-existant, as mentioned previously by McPherson (1972b).

Miller & Viessman (1972) suggest that the pervious areas of an urban watershed contribute to the runoff from large storms, probably beginning at 1.5 to 2.0 inches of rainfall, depending upon the hydrologic soil class. After the initial abstraction almost all the precipitation falling on impervious areas is converted to runoff. Consequently the impervious areas with their reduced losses will also increase the expected runoff from the larger rainstorms.

Now that the effect of impervious areas has been discussed the spatial location and the areal variation of these areas within urban centres can be considered. The coverage of impervious areas within an urban landscape can be commonly related to certain land-uses. Unfortunately the distribution of these land-uses varies not only between a city centre and its contiguous metropolitan area but also from one metropolis to another. McPherson (1972b) lists the
range of urban land-uses among seven of the largest American metropolises. These are shown in Table 2.14.

**TABLE 2.14**

**THE RANGE OF URBAN LAND-USES FROM AMERICAN CITIES,**

(from McPherson, 1972b).

<table>
<thead>
<tr>
<th>LAND USE</th>
<th>MINIMUM PORTION</th>
<th>MAXIMUM PORTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>Roads and Streets</td>
<td>1/6</td>
<td>1/3</td>
</tr>
<tr>
<td>Open Space and Recreation</td>
<td>1/20</td>
<td>1/4</td>
</tr>
<tr>
<td>Commercial, Industrial, Institutional and Mass Transportation</td>
<td>1/8</td>
<td>3/10</td>
</tr>
</tbody>
</table>

Furthermore, within each of these urban land-uses the extent of impervious coverage varies considerably depending upon its actual situation in relation to the city centre. For example, Stankowski (1972), using six urban and suburban land-use categories, estimated the average percentage of impervious area for each land-use. This average had three different values depending on the location of the specific land-use. The "high" value was calculated for those land-uses within the central city neighbourhoods; the "intermediate" value was determined for suburban neighbourhoods; and lastly the "rural" value represented a rural or near rural environment. For the actual values of
imperviousness within each land-use, see Table 2.15.

TABLE 2.15

THE VARIATION IN IMPERVIOUSNESS IN DIFFERENT LAND-USE CATEGORIES, (from Stankowski, 1792).

<table>
<thead>
<tr>
<th>LAND USE</th>
<th>PERCENTAGE IMPERVIOUSNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Single-family residential</td>
<td>12</td>
</tr>
<tr>
<td>Multi-family residential</td>
<td>60</td>
</tr>
<tr>
<td>Commercial</td>
<td>80</td>
</tr>
<tr>
<td>Industrial</td>
<td>40</td>
</tr>
<tr>
<td>Public and Quasi-public</td>
<td>50</td>
</tr>
</tbody>
</table>

It follows that the effect of imperviousness can vary over a considerable range because in the first case its varying influence on different precipitation events and in the second case because of the varying extent of these areas in different urban locations.

2.2.2 Drainage Channel Characteristics.

The most obvious change in the surface drainage pattern brought about by urbanisation is the replacement of naturally flowing open channels by underground storm and combined sewers. Figure 2.20 illustrates a 68 sq.km. section of the Rock Creek watershed near Washington D.C., in Maryland.
REDUCTION OF TRIBUTARY CHANNELS

DUE TO URBANISATION, (after McPherson, 1972b)

FIGURE 2.20
The area in 1913 is shown in 2.20(a), when it was still rural and maintains a relatively large number of small, but open tributaries. Figure 2.20(b) shows the same area in 1966, now covered by an intensely populated suburban area which has an extensive installation of underground storm sewers. Of the 103 kms. of naturally flowing stream channels that existed in 1913, only 42% could be found above the ground in 1966.

TABLE 2.16

DENSITY OF UNDERGROUND DRAINAGE CONDUITS
IN SOME MAJOR CITIES
(from McPherson, 1972b, p.160)

<table>
<thead>
<tr>
<th>City</th>
<th>Area of City (A, sq.km)</th>
<th>Total length of storm and/or combined sewers (L, km)</th>
<th>L/A (km/sq.km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston, Mass.</td>
<td>124</td>
<td>2,190</td>
<td>17.6</td>
</tr>
<tr>
<td>Chicago, Ill.</td>
<td>580</td>
<td>5,786</td>
<td>10.0</td>
</tr>
<tr>
<td>Detroit, Mich.</td>
<td>360</td>
<td>4,656</td>
<td>13.0</td>
</tr>
<tr>
<td>Los Angeles, Cal.</td>
<td>1,191</td>
<td>1,389</td>
<td>1.2</td>
</tr>
<tr>
<td>Milwaukee, Wis.</td>
<td>246</td>
<td>2,205</td>
<td>9.0</td>
</tr>
<tr>
<td>New York, N.Y.</td>
<td>829</td>
<td>6,650</td>
<td>8.0</td>
</tr>
<tr>
<td>Philadelphia, Pa.</td>
<td>337</td>
<td>4,023</td>
<td>12.0</td>
</tr>
<tr>
<td>St. Louis, Mo.</td>
<td>160</td>
<td>1,796</td>
<td>11.2</td>
</tr>
<tr>
<td>San Francisco,</td>
<td>114</td>
<td>1,400</td>
<td>12.3</td>
</tr>
<tr>
<td>Washington, D.C.</td>
<td>158</td>
<td>2,816</td>
<td>17.8</td>
</tr>
</tbody>
</table>

There are over 300,000 kms. of storm and combined sewers in the USA. It is therefore not surprising to find that the total lengths of underground drainage conduits dwarf those...
of the open water courses in major cities. Table 2.16 shows some examples of the density of underground conduit drainage in major American cities. The ratio of the total sewer length to the area of the city, an urban equivalent of the drainage density, ranges between 8 and 18, except for Los Angeles which makes more extensive use of open channel drainage than the other cities cited. These figures are, generally speaking, higher than those commonly calculated for natural basins.

Strahler (1957) examined a series of basins under different lithological conditions and within certain physiographic regions of the USA. The lithologies included the resistant, massive Carboniferous sandstones of the Appalachian Plateau, Pennsylvania; the igneous-metamorphic and Pleistocene complex of the Coast Range in Southern California; and the badland topography in Arizona and New Jersey. The 15 basins analysed in the Appalachians produced low drainage densities between 2.5 and 4.375 kms. per sq.ml. Whereas the drainage densities of 27 basins in Southern California ranged from 6.25 to 8.125. Only the badland topography produced densities greater than the urban equivalents listed in Table 2.16. Three basins in Arizona produced densities between 125 and 187.5. This is because of the unique interference of man in disrupting the once stable soil mantle.
The catchment sizes of sewered drainage areas are generally much smaller than those of the natural streams passing through major urban areas. Table 2.17 shows the sizes of some urban drainage areas, which indicates for example, that in San Francisco the median catchment area of 0.77 sq.km. maintains approximately 9.5 kms. of sewers. This implies that the underground drainage systems replace mostly the smallest natural channels because the natural catchment boundaries tend to be preserved when subsurface drainage systems are provided. The dense network of underground channels rapidly removes runoff producing shortened lag times and heightened peak discharges.

**TABLE 2.17**

**STORM WATER DRAINAGE-CATCHMENT AREA-SIZE DISTRIBUTIONS FOR SOME MAJOR CITIES,**


<table>
<thead>
<tr>
<th>City</th>
<th>Total Area of City, sq.km.</th>
<th>Number of Catchments</th>
<th>Largest Drainage Area, sq.km.</th>
<th>Average Drainage Area, sq.km.</th>
<th>Median Drainage Area, sq.km.</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco</td>
<td>114</td>
<td>42</td>
<td>17.5</td>
<td>2.27</td>
<td>0.77</td>
</tr>
<tr>
<td>Washington</td>
<td>158</td>
<td>93</td>
<td>25.0</td>
<td>1.52</td>
<td>0.26</td>
</tr>
<tr>
<td>Milwaukee</td>
<td>246</td>
<td>465</td>
<td>7.4</td>
<td>0.39</td>
<td>0.10</td>
</tr>
<tr>
<td>Houston</td>
<td>1150</td>
<td>1283</td>
<td>10.3</td>
<td>0.26</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Although the majority of storm drainage conduits have small hydraulic design capacity and usually serve only small tributary areas, because they are so numerous they
transport storm runoff from most of the metropolitan area. For example, from 70 to 90% of the total areas of Milwaukee, Washington, San Francisco, and Philadelphia are drained by sewered catchments, (Tucker, 1969).

The rapid hydrologic response of most urban catchments is not only the result of the dense network of underground conduits and the large proportion of the city drained by sewers, but also because of the increased efficiency with which these channels convey runoff. Man-made conduits and street gutters have a much lower frictional resistance than the natural minor rills which formed the definite watercourses and ephemeral channels in the original catchment areas that they mostly replace. In addition, nearly all major cities use improved natural channels or excavated purpose-built channels for the collection of storm water from drainage conduit outlets. McCuen & James (1972) calculated that for the 64 sq.ml. urban catchment of Pond Creek, the fraction of the total channel length in an artificially improved state increased from 18.6% in 1946 to 56.7% in 1966. All these channels expedite the collection and concentration of the streamflow. For example,
"dramatic increases in peak runoff have been documented for some partially and even lightly sewer ed catchments, it appears likely that the increased peaks could be caused by the acceleration of flow afforded by the lower frictional resistance of streets and conduits, although the role of changed aggregate channels lengths is clearly uncertain," (McPherson, 1972b, p.17).

Consequently, a number of differing reasons have been presented to account for the changes in streamflow caused by urbanisation. The interrelated nature of these urban components preclude the separate evaluation and the relative importance of these factors with any great precision. This problem has certainly been enhanced by the enormous variation in urban landscapes as regards the extent of impervious areas, the size and density of sewer networks, as well as the type of main channel improvement. So, in conclusion, one could agree with Brater & Sangal (1969) who stated that:

"There is a need to develop more meaningful measures of the type and degree of urbanisation along with the improvement in the hydrological techniques," (p.212).

2.3 Methods of Measuring Urban Parameters.

The most commonly used expression to account for urbanisation in hydrologic studies has been the amount of impervious area as a percentage of the total drainage basin area. There are, however, at least four different methods by
which this "degree" of urbanisation may be attained and these are considered, in turn, below.

2.3.1 Planimetering Method.

The planimetering method and the land-use sampling technique may certainly be considered as conventional methods and, for a geographer, the most common methods of determining areal extent and proportion. Unfortunately, the literature is normally at best ambiguous, and in some cases totally silent in regard to the method of determining the urban parameters. For example, in a geographical study on the impact of suburbanisation on fluvial geomorphology, Graf (1975) implied that areas of disturbance, his urban parameter, were measured by a planimetering of photo-derived maps. This was indeed the case, being confirmed by a written communication, [8]. However, a similar implication can be interpreted from the work of Hollis (1974). In this case Hollis [9] established that the method of measurement as a stratified random un-aligned dot sampling technique, which is described by Berry and Baker (1968).

For a small basin (0.70 sq.km.) in Peterborough, Ontario Taylor (1975) measured the impervious area by delimiting all such surfaces on a large scale map while in the field [10]. These areas were then measured using a planimeter and expressed as a percentage.
The major problem with planimetering is the excessive labour input unless extremely sophisticated and expensive equipment can be employed. As an example, Graham et al. (1974) used infrared colour aerial photographs and a computer controlled electronic planimeter to measure impervious surfaces. This excessive input will, however, in isolating and measuring each surface, produce a great amount of detail and yield an extremely accurate value. McCuen (1975) suggests that the method can produce results, "most often within 1% of the true value," (p.361). The method appears to be most appropriate for small catchments. Both aerial photographs and large scale maps can be used, accompanied if necessary, by field work to obtain satisfactory results.

2.3.2 Land-Use Sampling Method.

As the size of watersheds increase, the enormous labour and time inputs required to perform a planimetering technique becomes extremely large. It is viable to incorporate a sampling technique to estimate the different urban land-uses. As an example, Martens (1968) sampled directly from topographical maps (Scale 1:40000). The 20 by 30 inch sheets were already divided into 24 five by five-inch squares by co-ordinate or grid lines. These
squares were then sampled using a 100-point grid superimposed onto each section in turn. The impervious area as a percentage of the total was determined by counting the number of intersections that overlay impervious areas compared to the total number of intersecting points. Thus the impervious area of the 30.5 sq.ml. Irwin Creek, Charlotte was calculated to be 10.9%, using a total sample of 9,211 points, (Martens, 1968, p.10).

2.3.3 Empirical Relationships Method.

One of the major limitations confronting both the previous methods is the fact that the actual situation or information has to be already existing and identifiable in that it has to be mapped or photographed. However, many mathematical simulation techniques using such land-use characteristics as model parameters, are designed for the purpose of analysing or predicting the hydrologic effects resulting from future changes in land-use, especially the encroachment of urbanisation. Obviously in this case the previous two methods of measurement cannot provide the necessary land-use information because it has yet to be realised. Information regarding planned populations, housing census forecasts, and the like would be available from planning agencies for future development areas. Thus, Gluck
& McCuen (1975) devised some prediction equations which could relate land-use characteristics to this readily available information to determine future land-use situations. To do this, land-use categories were related to census tract data for some 92 tracts within the 132 sq.ml. Anacostia R. basin in Maryland. The census tracts provided the independent variables, listed in Table 2.18, which also depicts the correlation matrix constructed in a linear correlation analysis with the 'percentage of impervious area' as the dependent variable (Y). The matrix, which is useful for identifying the degree of linear association between the independent variables, indicates the most significant variable, with a value of -0.738, was (X5); the distance from the centre of Washington D.C.

The correlation matrix was then used with scatter diagrams to indicate some nonlinear relationships from which a nonlinear model predictor was developed. The calibrated equation (4.3) was derived to predict the percentage of impervious area and explains a significantly greater percentage of the total variation (27.8%) than the linear model illustrated in Table 2.18.
TABLE 2.18
THE CORRELATION MATRIX OF THE LINEAR MODEL
(from Gluck & McCuen, 1975).

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
<th>X5</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1 Population density</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2 Employment density</td>
<td>0.166</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3 Pop. &amp; Emp. density</td>
<td>0.722</td>
<td>0.802</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X4 Housing density</td>
<td>0.912</td>
<td>0.227</td>
<td>0.712</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X5 Dist. from Washington</td>
<td>-0.681</td>
<td>-0.281</td>
<td>-0.609</td>
<td>-0.576</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Y % of Impervious area</td>
<td>0.730</td>
<td>0.388</td>
<td>0.714</td>
<td>0.675</td>
<td>-0.738</td>
<td>1.000</td>
</tr>
</tbody>
</table>
\[ I = 10.06 + 58.28 \left( \frac{0.00128P}{1 + 0.00128P} \right) - 1.258(D - 10.06) \] (Eq. 2.19)

where, \( P \) = population density, (people/sq.ml.);
\( D \) = distance from the CBD, (mls.).

(CBD represents the nearest city centre).

Although these prediction equations require considerably less labour input than either of the two conventional methods, and use readily available data the standard error of the estimate may be in the order of 7%, (6.27% for the impervious area estimate) and this may be considered its greatest drawback, (McCuen, 1975).

2.3.4 The Weighted Means Method.

Harris & Rantz (1964) first used an averaging technique which involved the estimation of the mean impervious area for each of several types of building construction. Then, the numbers of each type of building construction was obtained from aerial photographs and the total area of imperviousness for each type could be determined by multiplying by the respective mean impervious area. A summation of the total estimate for each type produced the total impervious coverage for the study area.
Hollis (1974) carried out a similar procedure calculating the mean area of impervious surface per dwelling in each of the neighbourhood units, and multiplying this value by the total number of dwellings in that unit. The summation of the figures for all the neighbourhoods produced the total area of impervious surface for the catchment. Whereas Harris & Rantz averaged the type of building, Hollis averaged the area of the buildings within each neighbourhood. However the time and expense required to use these techniques and the employment of large scale maps or aerial photographs may hinder or preclude altogether the estimation of impervious area by this method. However, once a typical situation has been measured the results may be re-applied in other areas of similar urbanisation.

2.4 A Summary of the Literature.

First of all, the effect of urbanisation on a number of streamflow components can be summarised:

Time Distribution variables are reduced. In a number of studies, 'lag time' was shown to decrease by over 80% from its original 'rural' value.

Peak Discharge, measured by hydrograph analysis, was increased. Studies using the Unit Hydrograph analysis showed that the increase in peak discharge ranged between 1.5 to
4.0 times its former 'rural' value. Similarly, flood frequency analysis showed that the Mean Annual Flood increased by similar proportions. From the research of Anderson, D.G., (1970), Wilson, (1967), and Martens, (1968) extrapolations representing a basin with 100% impervious cover would increase the flood from 2.5 to 7.68 times its original value depending upon the urban conditions.

The increases recorded in the low frequency floods were a matter of some dispute mainly because of inherent difficulties in handling the short length of records that appear to characterise most urbanised catchments. Generally, the relative increase in a low frequency flood was shown to be less than that for a higher frequency. However, the increase in absolute terms varied somewhat. For example, Hammer (1973) suggested the effect of urbanisation was still substantial at a 100-year recurrence interval whereas Martens (1968) indicated that at this frequency the effect was negligible.

Runoff Yield was generally increased, even though the role of soil moisture and groundwater is reduced. This increase is the result of runoff responses from moderate and small precipitation events which would be entirely absorbed under 'rural' conditions.

The interference of urbanisation with infiltration characteristics is epitomised by the fact that runoff from
impervious surfaces, common urban features, is almost 100% of the precipitation from small events; only initial losses to depressional storage are incurred during such an event. The result of this interference increased the runoff yield from rainstorms as noted above. The variation in the amount of impervious surfaces within certain urban locations and for particular urban land-uses is also reviewed. However, the effect of this variation on the streamflow has not been documented within as there appears to be a dearth of literature on this aspect. The effect is, however, implied in that a particular urban situation can produce a greater or lesser effect, depending upon its properties. For example, the amount of imperviousness contained within that situation can be estimated knowing its location and the types of land-uses. Determination of the degree of influence can then be attained from a table based on empirical studies such as those constructed by Leopold (1969), Figure 2.15.

Urban areas appear to maintain a denser network of channels compared to many natural basins. Many surface channels are, either replaced by underground sewer networks, or artificially improved to facilitate the transport of stormwater. Storm drains and sewers also operate at a higher efficiency in transporting stormwater. These factors all combine to quicken the lag times and to heighten peak discharges.
Lastly, the merits and shortcomings of four different methods of measuring urbanisation are presented so that the most convenient method may be selected for the study particularly in relation to the availability of materials.
3. THE METHODOLOGY FOR THE CASE STUDY.

The research presented hereafter attempts a case study analysis of the effect of urbanisation on streamflow within Southern Ontario by comparing the monthly streamflow from urban catchments with the corresponding streamflow from a nearby rural catchment in order to detect a difference between them, and to subsequently identify where that difference occurs. In order to carry out this analysis a certain methodology has to be established. This methodology is outlined in this chapter and includes:

a) the physical arrangement adopted in order to carry out the analysis;

b) the type of database that was to be acquired and analysed;

c) the selection of catchments from those within Southern Ontario, bearing in mind the imposed limitations set by the constraints of the physical arrangement and the availability of data;

d) the method of measuring the urbanisation within those catchments to which this applies;

e) the description of the characteristics of each of the selected catchments;
f) a description of each type of analysis that was performed and the actual procedure employed to carry out each analysis. These analyses included a statistical test, time series and trend analysis, and a flow duration analysis.

3.1 The Physical Arrangement for the Study.

The Literature Review indicates that the majority of studies use the second approach discussed by Esprey, Winslow & Morgan, (1969, p.216) which involves a direct comparison between existing urban and rural watersheds which are assumed to be hydrologically similar except for the effects of urbanisation. This study adopted this procedure and further refined the scope of the study by applying this procedure to one of the physical arrangements recognised by Snyder (1971), the "paired watershed method". In fact, this arrangement has been used by McCuen & James (1972) who examined the changes in annual peak flows from an urban catchment (Pond Creek, near Louisville, Kentucky) and from a nearby rural catchment, (Nolin R.).

From this arrangement "pairs" of data are provided, one item of the pair from the control watershed (rural), and one from the treated watershed (urban). Differences between the pairs of data can be detected and analysed. Although the
detection of differences presupposes that the differences between control and the treated watershed will result in differences in the streamflow from those catchments, the implication is that these differences are the result of the altered state, that is from a rural to an urban condition.

3.2 The Type of Database Incorporated in the Study.

Because of the basic common motivation to provide practical information that lies behind the majority of urban hydrologic studies reviewed, there is an almost ubiquitous feature regarding the type of data collected. The acquisition of data on variables controlling the urban runoff process centres upon various measurements of discrete, individual precipitation events and their resultant storm runoff hydrographs. The only exception mentioned in the Literature Review is performed by James (1965), who synthesised a continuous hydrograph series.

The use of storm based data has resulted in a concentration of research on understanding the factors which determine the shape of the hydrograph. This has resulted in a detrimental effect on research analysing the factors affecting the volume of runoff. Consequently, this study will attempt to investigate the effect of urbanisation on volumes of runoff, using a monthly time base rather than the
more commonly used storm unit time base. The feasibility of using this monthly time base was initially investigated by consulting a map of Active Hydrometric Stations from the Department of Environment, dated December 1972, that indicated an extensive gauging station network within Southern Ontario. The location of a number of gauging stations within this network presented the strong possibility of providing the necessary monthly streamflow records from an 'urban' catchment and from a neighbouring rural one. These catchments were situated within and around a number of urban centres including Toronto, Hamilton, Burlington, London, and Kitchener-Waterloo.

However, further consideration was necessary in terms of the length of streamflow records from these possible catchments. This was carried out by consulting the Surface Water Data Reference Index (1975), which indicated that many of the records that could possibly be utilised because of their favourable locations were of approximately ten years in length. Such records provided the best compromise between a suitable physical arrangement of an urban with a proximal rural catchment and the provision of streamflow data, and as such they were considered as feasible sources of data.

In a hydrological study concerned with streamflow volumes corresponding meteorological data would also be required. Consequently, consideration was also given to the
availability of monthly meteorological data records. This was carried out by studying the network of meteorological stations and their records for Ontario, which was obtained from the Ministry of Natural Resources in Toronto [11]. The information provided by the Ministry included station locations, the length of their records and the types of meteorological observations that were taken at each station. The most appropriate meteorological observations for hydrological studies include precipitation, temperature, and evaporation records. Most of the meteorological stations maintained monthly precipitation and temperature records. In fact, the precipitation records normally included three different types; the monthly rainfall total in inches; the monthly snowfall accumulation in inches; and the total monthly precipitation; the latter being a combination of rainfall and snowfall that was measured in inches of equivalent rainfall. The network of meteorological stations proved to be of a greater density than the gauging station network and therefore provided adequate coverage around those gauging stations already deemed as possible sites within the stated physical arrangement. However, evaporation records were much less common but if the need arose they could conceivably be estimated by one of a number of different estimation techniques that calculated monthly evaporation. Thus, it appears that within Southern Ontario...
there were monthly streamflow and meteorological records (monthly precipitation and temperature data) of a sufficient length, situated within or proximal to urban areas and, could therefore be utilised for a case study of this type.

3.3 The Selection of Study Catchments.

The actual choice of catchments was mainly restricted by the limitations imposed by the physical arrangement and also by the quality of data that could be gathered from within such an arrangement. Matching the availability of suitable streamflow records, adequate meteorological data, and possible facilities to measure urbanisation, resulted in the choice of the Metropolitan Region of Toronto as being the most promising location to finalise the selection of suitable catchments.

Using 1:25000 scale topographical maps for the Toronto region the actively recording gauging stations were located and their catchments were delimited. Suitable urban catchments were found to be restricted to the Highland Creek and the Little Don River basins. These are located on Figure 3.1 with a suitable neighbouring rural basin, Cold Creek. Each of these catchments provided approximately 10 years of monthly streamflow records from 1964-1974, a selection of meteorological stations which are also shown on Figure 3.1,
FIGURE 3.1
THE LOCATIONS OF THE THREE CATCHMENTS IN RELATION TO THE BUILT UP AREA OF TORONTO.

<table>
<thead>
<tr>
<th>Built-up Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cold Creek Meteorological Station</td>
</tr>
<tr>
<td>2 Richmond Hill GEMC Meteorological Station</td>
</tr>
<tr>
<td>3 Ellesmere Meteorological Station</td>
</tr>
</tbody>
</table>

Source: TORONTO 30 M 2 ed. (1980)
and finally both aerial photographic and topographical map coverage.

Table 3.1 presents some of the details of these catchments.

It should be noted that the flow at all three stations is described as "natural", Surface Water Reference Index, 1975 [12]. These catchments allowed the study to extend its "paired watershed" arrangement to include a twofold comparison using two different catchments with "changed land-use" conditions. This could increase the possibilities of detecting any hydrologic change or difference since the extent of the changed land-use would be increased.

A preliminary study of the extent of urbanisation, afforded by the 1:25000 Topographical map series, indicated
that the amount of urban built-up area in each urban catchment increased considerably during the 10 years of streamflow records, from 1964-1974. Thus, each urban catchment illustrated transitional changes in land-use. The possibility now arose of detecting hydrologic change or differences between the pairs of catchments and also the further possibility of attempting to relate, in some way, the extent of that hydrologic change to the changing extent of urbanisation. It was thought that if a difference or change could be illustrated, and that the nature of that difference could be determined, there existed the possibility of isolating and determining, to some extent, the influence urbanisation exerted on the streamflow from these catchments.

3.4 The Method of Measuring Urbanisation.

Having selected the catchments within which urbanisation may be shown to influence monthly runoff volumes, the measurement of that urbanisation may be considered. The Literature Review tends to suggest that the most commonly used urban parameter to describe urbanisation is the area of imperviousness as a percentage of the total catchment area. This parameter is one of the more easily measured parameters; being measured by all the methods described in
Section 2.3. In addition, this study attempts to analyse streamflow measured at a monthly time interval. This centres the research on streamflow volumes rather than on the time distribution or hydrograph shape aspects of runoff. Section 2.2 discussed the importance of impervious surfaces on the infiltration characteristics of a catchment, which in turn influences the streamflow volumes from that catchment. Consequently, imperviousness would be a suitable parameter with which to describe urbanisation in a hydrological study concerning runoff volumes.

The aerial photographic coverage over Toronto, at a scale of 1:4800, provided the facility to employ the conventional techniques of measurement. Because two of the catchments in the study, totalling 74 sq.mls., required a determination of the urbanisation within them, it was estimated that a minimum of 26 individual photographs would have to be analysed for each time a photographic sweep was performed over Toronto Metropolitan area between 1964 and 1974; the period covering the streamflow records of the catchments. This estimate assumed that each photograph, measuring 22 * 22 inches, covered about 2.78 sq.mls. and that the photographic coverage coincided exactly with the catchment boundaries. Evidently the actual number of photographs to be analysed in each sweep would be expected to be greater than this minimum estimate.
The time required to analyse the appropriate photographs using the planimetering method was considered to be too great and it was decided to perform a sampling survey to establish the amount of imperviousness within each catchment. In using the sampling technique a compromise between the amount of time spent gathering the information and the accuracy and detail of the sampling analysis was attained and this resulted in the following sampling procedure.

The photographs were sampled individually using a 121 point, eleven by eleven, square grid. Thus each point represented an actual area of 4 sq.ins. and an area over the ground of 0.023 sq.mls., (640,000 sq.ft.). This sampling resulted in a theoretical sample of 2,176 points for the 50 sq.ml. Little Don catchment and a 1,480 point sample for the 34 sq.ml. Highland Creek catchment. The adjacent photographs, however, overlapped between 30% and 35% of their area. To compensate for this, the outermost sample points on the right hand side and on the bottom of each photograph were recorded. Then the same sites were located on the photograph adjacent and to the right of the original and were used as principal points to reposition the grid and to continue the sampling. These principal points had already been sampled on the previous photograph and so were omitted from the sampling on the present photograph. This helped to
prevent the sampling of the same area twice, when considering the overlapping portions of adjacent photographs. In this manner the grid was transferred to each photograph in turn to complete a sampling procedure for the whole catchment. To record the sampling an identification number, the total number of points sampled, the number of points located on impervious surfaces, and the number of points on all other surfaces was gathered for each photograph. Unfortunately, the Robarts Library, University of Toronto, where the sampling was performed, did not have a complete set of annual aerial photographic sweeps for the Toronto region and furthermore some of the years lacked complete coverage in that, the northern portion of the Little Don catchment had been omitted. This resulted in only 1964, 1967, 1969 and 1972 yearly coverage being used in the sampling.

To give an approximate indicator of the rate of growth of imperviousness within each catchment, throughout the study period, a least squares evaluation was also performed on the results from the four samplings from each catchment.
3.5 The Description of the Catchments.

After considering the measurement of urbanisation, the major distinguishing factor, it appears appropriate to present a brief description of those characteristics which are considered as similar under the assumption of the physical arrangement pertaining to this study. This description outlines the physiography and soil characteristics of each catchment as they normally play an important general role in determining streamflow, although it is appreciated many other factors also influence catchment runoff. This may help to establish the assumed similarities between the catchments and also help in the interpretation of the differences in streamflow by isolating urbanisation as the sole major difference between the catchments. On the other hand, it may emphasise the fact that urbanisation is not the only difference between the catchments and therefore not the only factor causing a difference in streamflows; even though it may be the most important one.

Over the entire Toronto area the bedrock is covered by a thick mantle of recent drift deposits that are associated with the Pleistocene Ice Age.
FIGURE 3.2
These overlying deposits have been classified throughout Southern Ontario by Chapman & Putnam (1973) on a physiographic basis. Figure 3.2 shows their physiographic classification for the area around Toronto. The relief around Toronto can be discussed in terms of four regions, identified by Chapman & Putnam; the Iroquois lake plain, the Peel plain, the South Slope and Oak Ridges.

The first region, the Iroquois lake plain, occupies the lowest levels being under 400 feet, and has a northern limit that is marked by an old shoreline, shorecliffs, and bluffs, which have been cut in the Pleistocene overburden. The plain itself, cut in previously deposited clay and till, is partly floored with sand.

"It is about three miles in width, sloping gently northward... Along its northern border are evidences of the old beach and a steep bluff or shorecliff which, in places is about 75 feet high. Beyond this the gently rounded hills of the till plain stand out at about 600 feet or more than 350 feet above the level of Lake Ontario," (Chapman & Putnam, 1973, p.328).

This old shoreline has been dissected by the Don and Humber rivers (Cold Creek) as well as Highland Creek. When the Iroquois stage of the Wisconsin glaciation ended and glacial retreat occurred the rivers resumed their downcutting to create incised valleys in the till plain.

The second region, the Peel plain is described as,
"a level-to-undulating tract of clay soils covering 300 square miles across the central portions of York, Peel, and Halton counties. The general elevation is from 500 to 750 feet above sea level," (Chapman & Putnam, 1973, p.292).

This plain can be approximately associated with Region 8, the bevelled till plains in Figure 3.2.

Separating the Peel plain from the Iroquois lake plain in this area is the Trafalgar moraine and adjacent till plain; part of the South Slope region. This region also encircles the Peel plain to the north, separating it from the Oak Ridges region, an interlobate moraine situated, in part, in the north of this area. The South Slope region approximates the area associated with Region 6, the till plains, shown on Figure 3.2. In the north, west of Maple, the surface is morainic; most of it being a ground moraine of limited relief. To the east of Maple the Slope is smoothed, faintly drumlinised, and scored at intervals by the river valleys. South of the Peel plain, in Scarborough township, there is a gently rolling till plain exhibiting bold flutings, while westwards in Toronto and beyond this type of surface fades out in favour of ground moraine with its irregular knolls and hollows.

The Little Don catchment spans the Peel plain with its northern and southern extremities within the encircling South Slope. The Highland Creek catchment is mostly contained within the southern portion of the South Slope.
where it is described as a rolling till plain. However, the south-eastern corner of the catchment has cut down through the old shoreline onto the Iroquois lake plain. The rural Cold Creek catchment, on the other hand, is situated partly within the northern section of the South Slope region and also includes, along its northern margins part of the Oak Ridges moraine.

The major difference between the catchments in regard to their physiography is within the Highland Creek catchment which includes part of the Iroquois lake plain and the old shoreline separating the lake plain from the till plain above. This proximity to the old shoreline, which is up to 75 feet in places, would suggest a more rapid downcutting or incision by the Highland Creek compared to that experienced in the Little Don and the Cold Creek catchments, which are further away from the shoreline. One could anticipate that as a result the slope of the Highland Creek is greater than the Little Don River and would therefore remove runoff more rapidly. The Literature Review indicates that channels slopes are particularly important in determining the time distribution component of streamflow; especially for individual storm events. However, the volume of runoff, (being considered herein), is not greatly influenced by channel slope which determines the speed and timing of that runoff. The majority of the remaining physiography can be
tentatively considered as hydrologically similar, being mainly comprised of till plains and till moraines of relatively gentle slopes.

Hoffman & Richards (1953) performed a soil survey in Peel County from which most of Cold Creek soil series could be determined. By 1955 the remainder of Cold Creek and the other two catchments were surveyed within the York County survey, (Hoffman & Richards, 1955). These surveys showed that the soils within all the catchments are contained wholly within the Grey Brown Podsolic and the Dark Grey Gleisolic soil classes. The predominant soil class in all three catchments is the Grey Brown Podsolic, but the soil types vary from clays to sandy loams, (see Figure 3.3). The glacial drifts, which in the Cold Creek catchment are mainly kame and till moraines, as well as till plain deposits with a characteristic morainic appearance, have resulted in loamy soils varying from the widespread King Series, described as a clay loam, to a sandy loam of the Pontypool Series, which is concentrated within the western extremity of the catchment.

In the Little Don catchment there is a greater variety of soil types that in the main appear to exhibit a greater proportion of clay particles, as a soil constituent.
FIGURE 3.3
THE SOIL TYPES WITHIN THE THREE CATCHMENTS,
SURVEYED IN 1953 AND 1955,
(derived from Hoffman & Richards).

<table>
<thead>
<tr>
<th>CLAY</th>
<th>CLAY LOAM</th>
<th>LOAM</th>
<th>SANDY LOAM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Highland Creek Catchment

Cold Creek Catchment

Little Don Catchment

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A large central portion of the catchment is covered by clays; the Peel Series and the Cashel Series being examples. The clay content is also maintained in the form of clay loams. For example the Chinguacousey Series and the Oneida Series are situated mainly on the western side and towards the upper part of the catchment. The dominance of clay-based soils can be explained by the till of boulder clay of the Peel plain, which is described as,

"heavy in texture and more calcereous than the underlying shaley till, having presumably, been brought by meltwater from the limestone regions to the east and north, and deposited in a temporary lake,"

In the Highland Creek catchment loams are by far the predominant soil type; the most common series being the Milliken Series, followed by the Wolburn Series. These loams cover the whole of the northern portion and most of the eastern side of the catchment. In the southern portion of the catchment the loams are replaced by sandy loams, again of the Woburn Series and also of the Fox Series, where the influence of the Iroquois lake plain becomes apparent.

The soils of all the catchments are mainly comprised of the Grey Brown Podsolic soil class. The soils include clays, loams, clay loams, and sandy loams. However, the major difference in the soils, which play a significant role in the rate at which precipitation will be converted to a form of runoff, is found in the Little Don catchment. Here, there
is a dominance of clay soils, probably where part of the Peel plain is enclosed by the catchment. The clay soils would tend to inhibit the absorption of water compared with the loams, particularly the sandy loams, thereby increasing the proportion of precipitation that is rapidly removed from the catchment. The relative resistance to absorption by these clays would also tend to increase the volume of water that is rapidly removed from the catchment. However, the differences between the clays and the loams, in terms of their hydrological properties, can be considered to be relatively insignificant when streamflow is considered in the aggregated unit of mean monthly discharge.

In conclusion, it must be stressed that this is only a brief examination of these catchment characteristics and as such does not attempt to explain the hydrological implications of all the differences indicated. However, it provides a perspective in which to view the effect of urbanisation on streamflow in that the general catchment characteristics of physiography and soils are very similar and those differences considered have a very limited potential in effecting the monthly streamflow.
3.6 The Procedure for a Preliminary Statistical Analysis.

The types of analyses and the procedures employed to attempt to illustrate differences in the streamflow from the urban and rural catchments are now considered. For each analysis, an introduction discussing the use of each step as a progressive development is outlined. A brief review of the concept of each analysis follows, and finally the actual procedure used to analyse the data is presented.

By creating the situation of a rural versus urban environment it is appropriate to begin the analysis with a statistical comparison of the streamflow record from the changed land-use (urban) with that of the pre-existing one (rural), in order to establish whether or not there is a significant difference between the hydrological responses from the different catchment conditions. Thus, the deliberation below selected the Wilcoxon Matched-Pairs Signed-Ranks Test for this comparison. The indication that there is a significant difference would certainly suggest a favourable climate in which to proceed with more detailed investigations.

Conversely, no significant difference between the streamflow records would promote the notion that the changed land-use (urbanisation) has not altered the hydrological response of the catchment, to any detectable degree, from
that under rural land-use conditions. The study is designed to exemplify the difference in the land-uses of the catchments, and one could anticipate that this would induce a difference in the streamflow responses of the catchments.

### 3.6.1 The Choice of Statistical Test.

Ideally,

"A method chosen to detect hydrologic change should be sensitive to change in the factor under consideration (mean monthly streamflow) and insensitive to violations of conditions on which the method is based," (McCuen & James, 1972, p.965).

However, there is at present an overwhelming domination of parametric statistical techniques in hydrology, which McCuen & James suggest are unsuitable, even inapplicable in urban hydrologic research. For example,

"The transitional nature of urban land-use change can cause violations of the conditions on which parametric statistical methods are based," (p.965), and also, "The validity of conclusions based on a parametric test depends upon the degree to which the conditions of that test are violated," (McCuen & James, 1972, p.966).

Thus nonparametric techniques, which are based on weaker conditions but can be used with limited amounts of data from population distributions of unknown characteristics, provide a convenient alternative to parametric methods. McCuen & James suggest a total of seven advantages that nonparametric tests have over the corresponding parametric tests, when
conditions of the latter are violated. Those which are most relevant to this analysis are cited below;

1) The computational effort required by most nonparametric statistical tests is considerably less than for a corresponding parametric test.

2) Probability statements obtained from most nonparametric tests do not depend on the shape of the population distribution.

3) Sensitivity to significant differences remains high when data are non-normal.

4) Significance probabilities are not much different when the data are non-normal.

Obviously, the first advantage is of great importance in a preliminary analysis of this type in that a relatively rapid procedure can determine whether the hydrological responses of the catchments differ to any detectable degree.

Consequently, a nonparametric test was used to test whether there was any significant difference between each of the two 'urban' streamflow records when compared separately with the 'rural' streamflow record. The Wilcoxon Matched-Pairs Signed-Ranks Test was used for this purpose, following closely the procedure adopted by Lazaro (1976). The monthly flows of each urban catchment were matched with the corresponding monthly flows of the rural catchment, creating pairs of data. The test not only utilises
information about the direction of the differences within pairs, but also the relative magnitude of the differences. Thus, the test not only indicates a change in mean values but also change in the central tendency (median value) of the two samples, or streamflow records.

3.6.2 The Procedure used to perform the Analysis.

In order to determine whether there is any difference between the two sets of data it is normal procedure to establish a Null Hypothesis (H0). Hammond & McCullagh (1974) state that,

"A null hypothesis is a negative type of proposition, formulated for the purpose of applying a statistical test to a problem under investigation, and generally in anticipation of being rejected as false," (p. 135).

In this situation the null hypothesis (H0) is defined as: there is no significant difference between the mean monthly streamflow of the urban and rural catchments. Thus the alternative hypothesis (H1) is defined as: there is a significant difference between the mean monthly streamflow of the urban and rural catchments. Because the direction of the difference is not specified, the test is, therefore, two-tailed.

In the first analysis, the Little Don streamflow record (urban) was tested against the Cold Creek record (rural) for
the period from Oct. 1964 to Dec. 1974. The corresponding mean monthly values were paired off and the difference \((d_i)\) between each pair was calculated. Thus the value \((d_i)\) corresponded with the \(i\)th pair of monthly values, see Appendix 2. Next the \((d)\) values were ranked in ascending order without regard to their sign. Thus the rank of 1 was assigned to the smallest \((d)\), the rank of 2 to the next smallest; so a \((d)\) of -1 was given a lower rank than a \((d)\) of either +2 or -2, (Siegel, 1956, p.76). A computer programme was devised to carry out the ranking procedure. It produced a listing of the rank number and its \((d)\) value side by side. The sign of the difference was then affixed to each rank, so that ranks arising from negative \((d)\)'s and those arising from positive \((d)\)'s were indicated, see the assigned rankings in Appendix 2, which shows the calculations for the test.

If the streamflow records were equivalent, that is, if \((H_0)\) is true, one should expect to find some of the larger ranks would come from positive \((d)\) values, while others would come from negative \((d)\) values. Thus, if all the ranks having a plus sign were summed together and all the ranks with a minus sign were also summed, one would expect the two summations to be about equal under \((H_0)\). However, if the sum of the positive ranks is very different from the sum of the negative ranks, one could infer that the streamflow records differ and \((H_0)\) would be rejected.
If the values of a single pair were equal the resultant (d) value would be zero. Such pairs were dropped from the analysis. If there were two or more (d) scores that were of the same value then the rank assigned to each (d) was the average rank for all those (d) values.

Then ranks with similar signs were summed and (T) was determined, such that,

\[ T = \sum R1 \]  (Eq. 3.1)

where, R1 = the smaller total of the two summations.

For large samples, where N (see Eq. 3.2 for definition) is greater than 25, Siegel (1956) suggested the calculation of a Z score using Eq. 3.2:

\[ Z = \frac{T - \frac{N(N + 1)}{4}}{\sqrt{\frac{N(N + 1)(2N + 1)}{24}}} \]  (Eq. 3.2)

where, T = the value from Eq. 3.1

N = the number of pairs whose differences indicated a sign.

The Z score is then applied to a table of probabilities (see Table 4.3) to determine whether the calculated probability is within the rejection region set by the critical or the rejection level already determined. From this (H0) can be either rejected or upheld.

The table actually gives one-tailed probabilities of Z under (H0). The left hand marginal column gives various values of Z to one decimal place. The top row gives values
to the second decimal place. The one-tailed probability of $Z$ can be determined by applying the calculated $Z$ score to the table. The two-tailed probability value is then calculated by multiplying the one-tailed probability by a factor of two.

3.7 The Procedure for the Time Series and Trend Analysis.

Following the application of the Wilcoxon Test which tested for a statistically significant difference between the streamflow records of the two urban catchments and the rural one, the next step attempts to determine the nature of an established difference. An examination of the monthly time series from the catchments could indicate periods where differences occur or where the differences are greatest. A trend analysis could indicate inherent trends in the monthly time series, differences in the trends expressing differences in the properties of the time series.

3.7.1 Time Series and Trend Analysis.

A time series can be recognised as having one or more of the following components:

1) the overall or long term trend; sometimes referred to as the secular trend;
2) periodic fluctuations of a rhythmic nature; usually associated with daily, seasonal, or other cyclic variations;
3) irregular or random variations; (Hammond & McCullagh, 1974, p.79).

Many statisticians, however, often refer to the data sequence as being 'noisy'. This implies that the observations consist of two parts; an underlying signal or meaningful pattern of variation, and a superimposed noise or random variation. Davis (1973) describes signals as being 'long-term', and that they tend to be the same from point to nearby point whereas the noise has no such tendency, being 'short-term' and fluctuating rapidly. A number of different schemes for determining the estimate of the signal value itself have been proposed; most are least-squares or weighted averages. All these schemes reduce the noise and in doing so produce a more gentle curve than the original data sequence. In using this technique it was hoped that the 'long-term' trend of the streamflow records could be illustrated, and thus indicate whether the individual records showed a decreasing or increasing trend and whether or not the trends differed between the catchments. This procedure is often called data smoothing or filtering as well as trend analysis.

The most common type of data smoothing is a simple moving average. The smoothed value (Y) is calculated by the
expression in Equation 3.3, which defines the interval centred around the point to be estimated.

\[
(\hat{Y})_i = \sum_{j=i-k}^{i+k} \frac{(Y)_j}{m} 
\]  

(Eq. 3.3)

where, \((\hat{Y})_i\) = the smoothed value to be estimated
\((Y)_j\) = a value in the original data sequence,
m = length of the smoothing interval or the number of points over which the average is to be made,
\(k = \frac{m - 1}{2} \)  

(Eq. 3.4)

It should be noted that \((m)\) must be an odd number for the estimated value of \((\hat{Y})_i\) to correspond with the central point within the smoothing interval. It soon becomes apparent that the longer the smoothing interval \((m)\) the greater the reduction in the variance or noise of the original data sequence. The smoothing analysis will also shift the peaks and troughs of the original sequence so that in effect a moving average sequence will "lead" an upward run in the original data; that is, the smoothed curve will rise at a greater rate than the original data themselves. Likewise, a smoothed curve will "trail" a downward run.
3.7.2 Procedure devised to apply the Trend Analysis.

In order to analyse the time series and to produce trend sequences of the streamflow records for the three catchments a computer programme, called SMOOTH, was extracted from Davis (1973). This was then debugged and slightly modified to run on a Xerox Sigma 7 computer; a listing of the programme is presented in Appendix 3. All the facilities of the original programme were maintained. This included not only the calculation of a specified smoothed sequence but also its graphical print-out from the line printer, using a subroutine called TSPLOT. The calculations of the variance of the original sequence and the smoothed sequence were also retained along with the percentage of the sums of squares accounted for by the smoothing process. This percentage describes approximately the actual effectiveness of the smoothing process. This programme was run repeatedly to obtain selected smoothed sequences of the catchment records. An example of the raw output produced by SMOOTH for the Cold Creek streamflow record and its 49 term smoothed sequence is illustrated in Appendix 4.

The values of the smoothing interval (m) were chosen to attempt to remove the seasonality that inherently occurs in a monthly time series and to illustrate any real underlying
trends in the data records without causing added complications in the interpretation of the smoothed sequences. To attempt to achieve this selective smoothing the 11 and 13 term smoothing intervals were used followed by the 47 and 49 term intervals. As the size of the smoothing term increased, naturally the length of the smoothed sequence became smaller. The 49 term smoothing produced a sequence which provided a sufficient number of data points that could be usefully related to the original series and was large enough to illustrate successfully any "long-term" trend in the streamflow records, while the 13 term smoothing approximated a 12 month interval or an annual smoothing interval in an attempt to remove the seasonality in the monthly data.

A graph was plotted showing the time series for each catchment and two superimposed smoothed sequences. The smoothed sequences from all the catchments were also plotted on the same set of axes so that they could be compared directly.

3.8 The Procedure for Flow Duration Analysis.

Using the previous analysis to establish the differences in the streamflow records in a time oriented perspective, flow duration analysis can be performed to attempt to
illustrate differences from the perspective of the discharge values themselves. This analysis examines the probability of certain discharges throughout the study period and is generally applied to hydrological studies concerned with water storage and reservoir problems, and as such may prove to be useful in examining runoff volumes.

3.8.1 Flow Duration Analysis.

The flow duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharges were equalled or exceeded in a given period. It is another means of representing streamflow data, combining in one curve the flow characteristics of a stream throughout the range of discharge. It can also be used for comparing one basin with another, (Searcy, 1959).

Thus, the flow duration curves for the two urban catchments could indicate flow characteristics that are distinctly different from those expressed in the rural catchment. By plotting the flow duration curves for all the catchments on the same axes their differences can be evaluated by a direct comparison. Certain hydrologic characteristics of the catchments may be emphasised by plotting the flow duration curves on arithmetic, logarithmic, or probability scales.
3.8.2 Procedure Adopted for the Analysis.

In this study the flow duration curve for each catchment was calculated by ranking the magnitude of the monthly flows throughout the study period and plotting the ranked values against a time scale on which the minimum flow is said to occur 100% of the time and the maximum flow to occur instantaneously or for less than 1% of the time. The actual calculations were computed using a computer programme called FLOWDUR (see Appendix 5), which ranked the data in ascending order and plotted a graph on the line printer using the subroutine, TSPLOT, (see Appendix 6 for a typical raw output).

All three flow duration curves were then plotted on a single set of axes so that they could be compared directly. Initially, arithmetic scales were used on both the x-axis and the y-axis because the analysis only required a comparison between the flow duration curves. However, Searcy (1959, p.11) suggested other scales can be used for specific purposes. For example, a logarithmic scale for discharge values conveniently accommodates the range of values especially when they cover three or four logarithmic cycles. For the same range of values an arithmetic scale would be undesirably small for all but the highest values. A
probability scale expands both ends of the flow duration curve so that normally distributed data plots as a straight line. As the logs. of discharge are more normally distributed than the discharge values themselves, the logarithmic - probability scales tend to straighten out the flow duration curve and facilitates the expression of the curve as a mathematical equation.

The data from the flow duration analysis was also plotted on logarithmic - probability scales in order to facilitate the division of discharges into 'high', 'medium', and 'low' categories of flow. This division was made by fitting least squares regression lines through appropriate parts of the flow duration curves and using the positions of these lines to determine the boundary values.

The occurrence of monthly discharges within these categories could then be examined for the whole year. Thus, for each month of the year the number of 'high', 'medium', and 'low' flows could be tabulated for each catchment. Certain months were then grouped together as "summer", "winter", and "snowmelt" periods and plotted as bargraphs. A comparison between the occurrence of flow categories within each catchment for those specified periods could be made.

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3.9 Summary of the Methodology.

This case study attempts to illustrate the effect of urbanisation on streamflow using three instrumented catchments situated within the Metropolitan Region of Toronto to ascertain the difference between the streamflow from two urban catchments from that of a nearby rural catchment. The physical arrangement of the study is described as a twofold comparison between two urban catchments and a nearby rural one using the assumption that the catchments are similar except for the alteration of land-use from rural to urban. Data averaged over a monthly time period was employed to construct these comparisons. Then the procedures adopted to carry out the analyses of this data are outlined. The first analysis, using the Wilcoxon Matched-Pairs Signed-Ranks Test to examine whether there is any difference between the urban and rural records is followed by a time series and trend analysis. This is followed in turn by a flow duration analysis. Both these latter analyses attempt to examine the nature of the differences in streamflow already indicated by the statistical test, which attempts to attribute those differences to urbanisation. The method employed to measure the amount of urbanisation with the urban catchments along
with a brief description of the physiography and soil characteristics of all the catchments is also presented.
4. THE RESULTS FROM THE ANALYSIS.

The results of each analysis are presented and discussed in sequence, beginning with the measurement of urbanisation and proceeding through the Wilcoxon Test, the time series and trend analysis, and finally the flow duration analysis. The measurement of urbanisation indicates the extent to which the urban catchments have been altered from the rural or pre-urban condition. Then the Wilcoxon Test establishes that there is a difference between the monthly streamflow of the urban and rural catchments, that difference being attributed to urbanisation. The subsequent analyses attempt to isolate the differences in the streamflow relating those differences to the presence of urbanisation. The time series analysis considers the streamflow as it occurred throughout the study period, a real time perspective, whereas the flow duration analysis concentrates upon the discharge values, using probability of occurrence as a relative time base.

4.1 The Measurement of Urbanisation.

The sampling procedure, outlined in Section 3.4, recorded the total number of points sampled, the number over impervious surfaces and the number over other land-uses, for each photograph covering the catchments.
TABLE 4.1
THE RECORDINGS OF IMPERVIOUS SURFACES WITHIN THE
HIGHLAND CREEK CATCHMENT FOR 1964.

<table>
<thead>
<tr>
<th>AERIAL PHOTOGRAPH NUMBER</th>
<th>TOTAL NOS. OF POINTS SAMPLED</th>
<th>POINTS OVER IMPERVIOUS SURFACES</th>
<th>POINTS OVER OTHER LAND-USES</th>
</tr>
</thead>
<tbody>
<tr>
<td>146</td>
<td>80</td>
<td>49</td>
<td>31</td>
</tr>
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<td>147</td>
<td>89</td>
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<td>10</td>
<td>35</td>
</tr>
<tr>
<td>171</td>
<td>31</td>
<td>11</td>
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<td>62</td>
<td>21</td>
<td>41</td>
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<tr>
<td>260</td>
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<td>7</td>
<td>32</td>
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TOTALS: 1482  283  1199

Percentage Area covered by Impervious Surfaces
= \( \frac{283}{1,482} \times 100 \) = 19.1%

Sampling Error
= \( \frac{2}{1,482} \times 100 \) = +0.14%
TABLE 4.2


THE LITTLE DON CATCHMENT

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Nos. of Points Sampled</th>
<th>Points over Impervious Surfaces</th>
<th>Percentage Error of Sample</th>
<th>Percentage of Imperviousness</th>
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</thead>
<tbody>
<tr>
<td>1964</td>
<td>2204</td>
<td>248</td>
<td>+1.28</td>
<td>11.4</td>
</tr>
<tr>
<td>1967</td>
<td>2125</td>
<td>310</td>
<td>-2.35</td>
<td>14.6</td>
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<tr>
<td>1969</td>
<td>2169</td>
<td>353</td>
<td>-0.23</td>
<td>16.3</td>
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<tr>
<td>1972</td>
<td>2186</td>
<td>501</td>
<td>+0.46</td>
<td>22.9</td>
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</table>

THE HIGHLAND CREEK CATCHMENT

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Nos. of Points Sampled</th>
<th>Points over Impervious Surfaces</th>
<th>Percentage Error of Sample</th>
<th>Percentage of Imperviousness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
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<td>+0.14</td>
<td>19.1</td>
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<td>1967</td>
<td>1452</td>
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<td>1972</td>
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<td>427</td>
<td>-0.21</td>
<td>28.9</td>
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</tbody>
</table>
An example of these recordings is presented in Table 4.1, which illustrates the results of sampling the Highland Creek in 1964., and indicates that 19.1% of the catchment was covered by impervious surfaces.

Similar recordings were taken for the remaining years and for the Little Don catchment. The results of those samplings are presented in Table 4.2. Only these two catchments were sampled because an examination of the rural Cold Creek catchment indicated that there were no conglomerations of impervious surfaces; for example, a village with a collection of streets and buildings. Consequently, a sampling procedure need not be performed as no urbanisation whatsoever was present. As indicated in Table 4.2, the sampling error varied from -2.35% to +1.28% in the Little Don catchment and from -1.90% to +1.42% in the Highland Creek catchment. This error is within an acceptable margin of error, particularly as the measurement of urbanisation was only used to give an indication of the extent of that changed state within each catchment.

The results from both catchments indicate an increasing trend of imperviousness throughout the study period. This is illustrated on Figure 4.1, which plots the results of Table 4.2 along an x-axis representing the length of the study period. The actual percentages were plotted in June, the month in which the aerial photograph sweeps were taken.
THE GROWTH OF IMPERVIOUS SURFACES IN THE TWO URBAN CATCHMENTS

HIGHLAND CREEK CATCHMENT

\[ Y = 18.655 + 0.106X \]

LITTLE DON CATCHMENT

\[ Y = 10.571 + 0.117X \]

The Study Period from 1964 to 1974
In order to establish an indicator of the rate of growth of imperviousness within each catchment, and also to express the percentages as a straight line approximation, a least squares evaluation was performed. Although the assumptions of the linear regression technique are not really applicable, the least squares evaluation was only used to express the rate of growth graphically as a straight line approximation.

From Figure 4.1, the slope of the line suggests that the expansion of urbanisation in the Little Don catchment proceeded at a faster pace than in the Highland Creek. The ratio between the Little Don and the Highland Creek percentages increased from 0.60 in 1964 to 0.79 in 1972, confirming the more rapid growth of imperviousness in the Little Don catchment.

In conclusion the amount of imperviousness in the Little Don catchment increased throughout the study period from 11.4% in 1964 to 22.9% in 1972, an increase of 11.5%. Similarly, in the Highland Creek, the amount of imperviousness increased from 19.1% in 1964 to 28.9% in 1972, an increase of 9.8%. So the major difference between these two catchments in the absolute amount of urbanisation within each catchment, although the greater rate of growth depicted in the Little Don catchment also indicates a more subtle difference.
4.2 The Wilcoxon Test.

First of all, differences between the streamflow records may occur because of the differences in the catchment sizes. Normally, a smaller catchment area will contribute a smaller discharge than that from a larger catchment. To remove this possible source of difference, and also making the discharge values directly comparable, the mean monthly totals were reduced to a unit area, such that the discharges used in all the subsequent analyses were measured in cubic feet per second per square mile [13].

In all these following statistical tests the rejection level was predetermined at the 99% level, ($\alpha = 0.01$). From the Table of Probabilities, see Table 4.3, the critical rejection level corresponded to a $Z$ score of 2.575. Thus, a $Z$ score of $> 2.575$ or $<-2.575$ can be included in the rejection region. This region consists of all $Z$ scores which are so extreme that the probability associated with their occurrence under (H0) is equal to or less than the critical value or rejection level, ($\alpha = 0.01$). Table 4.3 also indicates the probabilities that are within the rejection region when ($\alpha = 0.05$); a 95% significance level.
### Table 4.3

A Table of Probabilities Associated with Z Scores, (from Siegel, 1956).

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<td>.0001</td>
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#### Rejection Region at the 95% Significance Level

- **Value**
- **Rejection Region**

#### Rejection Region at the 99% Significance Level

- **Value**
- **Rejection Region**

*The Analysis 135*
In the first case, the comparison of the streamflow records the established (H0) stated that:

There is no significant difference between the streamflow records of each urban catchment and the rural catchment.

Since the direction of the difference is not specified the test is two-tailed.

Table 4.4 presents the results of comparing the Highland Creek and then the Little Don streamflow records (both urban) with the rural Cold Creek streamflow records. The detailed calculations are presented in Appendix 2, which also lists the mean monthly streamflow records for all the catchments.

**TABLE 4.4**

THE RESULTS OF THE WILCOXAN TEST ON THE URBAN AND RURAL STREAMFLOW RECORDS

<table>
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<tr>
<th></th>
<th>N</th>
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<td>Highland Creek</td>
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The Z score determined for the Highland Creek and Cold Creek records (-6.49) is smaller than the critical score (-2.575)
and is consequently associated with a probability that is within the established rejection region. Similarly, the Z score calculated for the Little Don and the Cold Creek records (-7.57) is also associated with a probability that is within the rejection region. It should be noted that the Z scores themselves correspond to such small probability values that they cannot be assessed using the Table of Probabilities in Table 4.3. However, the Z scores indicate that, in both cases, their associated probabilities are below the critical level (= 0.01), and thus the (H0) can be rejected. Consequently, there is a difference between the urban and the rural streamflow records, and therefore the Wilcoxon Test has indicated that both the Little Don and the Highland Creek records differ significantly from the rural Cold Creek monthly streamflow record.

These differences may, however, be the result of differences in precipitation that occurred over the catchments during the study period. To determine if there is any statistical difference between the precipitation over the catchments, the monthly rainfall totals from the Ellesmere meteorological station within the Highland Creek catchment were compared with the corresponding totals from the Cold Creek meteorological station within the rural catchment. Then the monthly precipitation totals from the Richmond Hill OWRC meteorological station within the Little
Don Catchment were compared with those from the Cold Creek station. It should be noted that the precipitation totals are comprised of both rainfall and snowfall records, expressed as equivalent inches of rainfall. The new (H0) established for these tests stated that;

There is no significant difference between the monthly precipitation data recorded in the urban and the rural catchments.

Because the direction of the difference is not specified the test is two-tailed.

A summary of the results of these tests is presented in Table 4.5, while the detailed calculations are presented in Appendix 7. These calculations include a listing of the monthly precipitation and rainfall totals for the study period where two corresponding months could be matched. The Z score (-1.26) calculated from the rainfall totals recorded in the urban Highland Creek and the rural Cold Creek resulted in a two-tailed probability of 0.2076. From Table 4.3 it can be seen that this probability lies outside the rejection region at the 99% level and the (H0) must be upheld. Similarly, the two-tailed probability of 0.1586, produced from the precipitation totals for the Little Don and the Cold Creek catchments, also lies outside the rejection region. The (H0) is again upheld.
<table>
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<th>Two-tailed Probability</th>
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</table>
It may be noted that in both cases the calculated probabilities also lie outside the rejection region established at a 95% significance level, see Table 4.3). Thus, one can conclude that there is no significant difference between the monthly precipitation totals over the catchments.

Consequently, the statistical difference established between the urban and the rural streamflow records cannot be attributed to differences in the precipitation received by the catchments over the study period. They may, however, be attributed to differences in catchment characteristics. By far the most important, established difference between the catchment characteristics, in terms of its effect on the hydrological response of the catchment, is that of urbanisation. Consequently, the differences indicated in the monthly streamflow records may be attributed to the presence of urbanisation. In establishing the importance of urbanisation in causing the difference, further investigations into the nature of the difference may identify the effect urbanisation exerts on the monthly streamflow from these catchments.
4.3 The Time Series and Trend Analysis.

For the sake of clarity the results from the time series will be considered separately from the trend analysis. The seasonality inherent in monthly series is clearly evident, illustrated by the high flows caused by snowmelt conditions that occur in the spring of every year, see Figures 4.2, 4.3, and 4.4. (The data from which these graphs were generated are included in Appendix 2). These high flows are generally followed by low summer and early winter flows. This annual cycle of discharge can be clearly traced throughout all the time series.

In Figure 4.2, the streamflow record for the Highland Creek catchment, for three years of the series (1966, 1967, and 1968) spring snowmelt peaks of approximately the same value, just above 2.0 cfs/sq.ml., are recorded. These are then followed by three consecutive peaks all of which are smaller in value than the previous four. These, in turn, are followed by the two largest spring snowmelt peaks of the series, in the spring of 1971 and 1972, which record discharges of more than twice those of the preceding three years. This grouping of high, low and then maximum peaks is also apparent in the other catchment records.
FIGURE 4.2

The Analysis 142
FIGURE 4.3

The Analysis 143
In the Little Don catchment, (see Figure 4.3), the first three spring snowmelt flows, from 1965-1967, are not significantly different from the middle three peaks between 1969-1971. Only the spring flow for 1968 stands out as a higher value, being almost 3.0 cfs/sq.ml. The latter part of the record, 1972-1974, does record the highest spring flows similar to the Highland Creek.

In the Cold Creek catchment, (see Figure 4.4), it is noticeable that all but two of the spring snowmelt flows are contained within one month's value, resulting in an isolated pointed appearance. This month is either March or April, with March holding a slight edge in the frequency of experiencing the snowmelt flows. In both the urban catchments many of the spring high flows are recorded over two adjacent months, producing a staggered, wider peaking.

The length of time over which spring snowmelt conditions occur, is approximately the same because one would suspect the conditions are mostly determined by the broad, overall climatic conditions. Therefore, in the rural catchment the spring snowmelt flows contribute, most of the time, to a single months' runoff, whereas the spring flows in the urban catchments contribute to the higher runoff volumes for two adjacent months, normally March and April. This infers that the snowmelt occurs over a slightly different time period than the corresponding snowmelt flows in the rural catchment.
FIGURE 4.5

THE MONTHLY DISCHARGES FOR THE PERIOD
FROM MAY TO DECEMBER 1971

MONTHLY DISCHARGE (cfs./sq.m.)

Highland Creek Discharges
Little Don Discharges
Cold Creek Discharges

May June July Aug Sept Oct Nov Dec
A larger difference between the monthly time series concerns the summer and winter flows. In the rural catchment the spring flows are followed by a continuous succession of low flows, excepting the singularity in the summer and winter of 1967, see Figure 4.4, where distinct peakings are evident. However, in the urban catchments the variation in these flows is much greater with frequent minor peakings appearing in both records. As an example of this difference Figure 4.5 shows the corresponding monthly flows from May to December 1971, for all three catchments.

For this period the monthly flows in the rural catchment vary from 0.28 to 0.40 cfs/sq.ml. while the flows in the Little Don catchment vary from 0.45 to 1.15 cfs/sq.ml. and those in the Highland Creek vary from 0.33 to 1.05 cfs/sq.ml. Not only is the variation in the flows over this period much greater in the urban catchments but also the volume of flow in all those months, with a sole exception, is greater than those in the rural catchment. This phenomenon can be traced, to a greater or lesser degree, throughout the whole of the study period and may prove to be a most significant difference between the urban and rural catchments.

To continue the discussion into the smoothed sequences two major points may be considered from the 13 term trends indicated in Figure 4.6.
(The data from which this graph was generated is presented in Appendix 8). First of all, there appears to be a common long wavelength cyclic component which is evident in all three sequences. This oscillation reaches its first maximum amplitude, or crest, at approximately the same time in all the sequences, September 1967, and then proceeds to decline into a trough or a minimum value in early 1970. It then arises to a crest again by September 1972. It seems possible that this phenomenon may reflect the variation in the spring snowmelt flows over the entire study period being, generally high in the years 1965 to 1968, then low from 1969 to 1971 and attaining the maximum values in the years 1972 to 1974. However, Yevjevich (1972) highlights one of the inherent dangers that can cause misinterpretation of these smoothed sequences.

The cyclic component indicated may be an 'optical error' which is solely the result of the application of trend analysis. This visual impression of an oscillating movement can be shown to be a random entity because the components of the oscillation, the amplitude and wavelength have a random variation. When this is the case the smoothing is said to exhibit the Slutsky-Yule effect, which has been defined as the phenomenon of a smoothed independent stationary stochastic series showing fluctuations that look similar to periodic movements, (p. 219, Yevjevich, 1972). However, in
Figure 4.6, it appears unlikely that this effect is evident because the urban sequences illustrate an increasing trend which denounces the stationarity and independence factors from the conditions defined for the effect. Furthermore, there appears to be a visual relationship between the time series and the smoothed values tends to establish a real oscillatory motion. It is, however, always purposeful to indicate the possible dangers that can arise from the application of these analyses.

In considering the cyclic component of the 13 term smoothed sequences, they are similar in value only throughout the first crest, beginning in September 1967 and declining into the subsequent trough by August 1969. Here all three sequences are in close proximity with the rural sequence peakings above both urban sequences in September 1968. Over the latter half of this period the rural sequence exhibits higher values than that from the Highland Creek.

In the troughs on either side of this crest, from September 1966 to August 1967 and from August 1969 to August 1971, the separation between the sequences is much greater. The rural sequence displays the lowest values in both troughs, but the Highland Creek sequence is continually highest in the first trough while the Little Don sequence is continually highest in the second trough. The separation between the two urban and rural sequences attains maximum
levels within the final section, from September 1971 to the end, June 1974. In fact, from 1970 onward the two urban sequences rise at a much more rapid rate than the rural sequence. Thus, the values within the second crest in the urban sequences are greater than those in the first. In the rural sequence this is not the case, the maximum values in both crests being approximately the same.

Finally, there is a difference between the urban sequences. The Highland Creek sequence maintains a higher value than the Little Don sequence from the beginning, April 1966 to October 1967. Then, during what is essentially the trough of the cyclic component the Little Don sequence is continually greater than the Highland Creek. After October 1971 the latter sequence then reverts back to its original status, above the former sequence.

The second major point concerns the small but distinct peakings that occur approximately every 12 months in all three sequences. This is the result of combining together two snowmelt flows from consecutive years, because of the 13 term smoothing interval. This combination results in a clearly defined peaking even though it is being averaged over another 11 months. This confirms the visual expression of the vast difference between the spring high flows and the following summer low flows that is presented in the time series graphs.
The extent of the difference between the high snowmelt flows and the surrounding lower winter and summer flows may be visually illustrated by the size of the peakings. The largest peaking in all three sequences occurs in September and October 1972 and is the result of the combination of the two largest snowmelt flows recorded in all the catchments in the springs of 1971 and 1972.

The major difference between the rural and urban peakings within their sequences occurs in September 1968 where a distinct rural peaking has no corresponding occurrence in either of the urban sequences. The Little Don sequence does show a rise that covers two consecutive points but the Highland Creek expresses a continual decline at this point. This could illustrate a breakdown in the distinct seasonality of the monthly streamflow within the urban catchments, a phenomena known to occur because of the effect of urbanisation. However, the urban sequences display peakings very similar to the rural ones throughout the rest of the study period and this tends to suggest that the seasonality still exists as a dominant factor in the monthly streamflow record.
THE 4C TERM SMOOTHED SEQUENCES FROM THE STUDY CATCHMENTS

- High Creek Catchment (urban)
- Little Don Creek Catchment (urban)
- Cold Creek Catchment (rural)

FIGURE 4.7
Finally, the 49 term sequences can be compared with an examination of Figure 4.7, which indicates very clearly the apparent trends evident in the time series graphs, Figures 4.2, 4.3, and 4.4, as well as those recorded by the 13 term smoothed sequences. (The data from which Figure 4.7 was constructed is presented in Appendix 9). Two major points can be considered; the differences in the direction of the trends and the differences in the values of the trends.

First of all, the Little Don sequence indicates a continually increasing trend, the rate of increase rising towards the latter part of the sequence. The Highland Creek sequence, however, shows a decline in the middle section illustrating a trough similar to those in the 13 term smoothed sequences. The Highland Creek sequence does maintain the higher values than the Little Don sequence at its extremities. Again, this is a similar circumstance to that illustrated in the 13 term smoothed sequences, (see Figure 4.6).

The rural sequence shows no apparent directional change although from approximately March 1968 to June 1969 higher values are recorded than those throughout the period from February 1970 to January 1972, with the exception of a peaking centred at March 1971. After January 1972 the trend increases again to approximately those higher values between March 1968 to June 1969.
Secondly, the values of the sequences are considerably different. The urban sequences record continuously greater values than those in the rural. This difference, because of the differing trends, increases in extent towards the latter part of the study period. The maximum range of the 49 term trend for the Little Don catchment covers 0.2831 cfs/sq.ml., from 0.7616 to 1.0447 cfs./sq.ml. while the increase in the Highland Creek catchment is from 0.7484 cfs/sq.ml. to 1.0086 cfs/sq.ml. The Cold Creek 49 term trend, on the other hand, indicates a variation from 0.6367 and 0.7182 cfs./sq.ml., a range of 0.0815 cfs./sq.ml. The Little Don sequence not only indicates a greater range but the minimum value occurs at the beginning of the sequence and the maximum near the opposite end, thus expressing a continuous increase. This is not the case in the rural sequence where the maximum and minimum values occur around the middle of the sequence, expressing no such directional inclination. As mentioned previously, the Highland Creek sequence declines to a trough in its middle section, which includes the minimum value. However, after that minimum, February 1970, a very rapid increase to the maximum value at December 1971 is evident.

The 49 term trend values could be defined as average flows, in a similar manner to that expressed by Hollis (1974),
"Finally, the mean maximum flood, as expressed by the 51-month moving mean, has increased from 1.16 to 2.58 cumecs [14], a rise of 220 per cent during the period under scrutiny," (p.127).

Similarly, then Table 4.6 presents the increase in the average flows in the urban catchments during the study period. The mean monthly flows have risen by approximately 36% and by 25% in the Little Don and the Highland Creek catchments respectively. The much smaller increases in flows compared with that expressed above by Hollis may be because he examined the maximum flows whereas the mean flows are being considered here.

**TABLE 4.6**

**THE INCREASE IN THE 'AVERAGE' FLOW WITHIN THE TWO URBAN CATCHMENTS DURING THE STUDY PERIOD.**

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<td>1st. 49-term value</td>
<td>0.8067</td>
<td>0.7616</td>
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<tr>
<td>Last 49-term value</td>
<td>1.0086</td>
<td>1.0337</td>
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<tr>
<td>% Increase in 'Average Flow'</td>
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<td>35.8%</td>
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</table>

In conclusion, the time series of the urban and rural catchments indicate differences in both the higher spring flows and the lower summer and winter flows.
A COMPARISON BETWEEN THE GROWTH OF IMPERVIOUSNESS AND THE 49 TERM SMOOTHED SEQUENCES WITHIN THE URBAN CATCHMENTS

The Analysis

1961

1965

1966

1967

1968

1969

1970

1971

1972

PART OF THE STUDY PERIOD (June 1964 to Dec. 1972)
The difference between the spring snowmelt flows is restricted to the apparent timing of the flows, indicated by the shape of the peaks in the time series; the values being approximately the same for all the catchments. The lower summer and winter flows, however, are different in their variation and their values. Throughout most of this time the urban catchments maintain a greater variation and greater values than the rural catchment.

These higher discharges are evident because of the consistently greater values of the smoothed sequences from the urban catchments, over most of their length. The difference in these values also increases towards the latter part of the study period, as the urban sequences illustrate an increasing trend whereas the the rural sequence shows no such tendency.

In fact, it is noticeable that the increasing trend of the urban sequences corresponds with the increasing growth of urban development in each catchment, which was measured in section 4.1. Figure 4.8 shows the urban development measured in each catchment along with the 49 term smoothed sequences. It indicates, for example, that a growth of imperviousness in the Little Don catchment from 11.4% in 1964 to 22.9% in 1972 was accompanied by an increase in the 'average' monthly flow of approximately 36%. Similarly, the 'average' monthly flow of the Highland Creek rose some 25%
as the percentage of imperviousness within the catchment increased from 19.10% in 1964 to 28.9% in 1972.

4.4 The Flow Duration Analysis.

Because of the close proximity of points that comprise the flow duration curves, especially between the urban catchments, only the points from the higher discharge values have been connected, see Figure 4.9. (The data from which this graph was constructed is presented in Appendix 10). A visual inspection of Figure 4.9 suggests two main aspects.

The first concerns the similarity in the flow duration curves of the two urban catchments, throughout almost their entire length. In the lower discharge values this similarity is particularly close, with the values from each catchment suggesting a common curve could be constructed, and indicating an almost constant rate of increase from 100% to the 30% mark. This similarity is in spite of the differing amounts of urbanisation that occurs within each catchment. Only below the 15% mark on the x-axis do the points separate to any degree. Here, the points from the Little Don catchment ascend at an almost constant rate, with higher values than the Highland Creek, (where the points are connected). This rate of ascendancy in the Little Don points continues until the 3% mark. Then the final three points indicate a very rapid ascent to the maximum value, (3.90).
THE FLOW DURATION 'CURVES' FOR THE STUDY CATCHMENTS

The percentage of time a given discharge is equalled or exceeded

**Figure 4.9**

- Highland Creek Catchment (urban)
- Little Don Catchment (urban)
- Cold Creek Catchment (rural)
On the other hand, the points from the Highland Creek indicate a less abrupt ascent, which, from the 9% mark is followed closely by the points from rural Cold Creek. This suggests a similarity between these higher snowmelt flows and helps confirm the results indicated by the previous analysis; that these flows only differ to any extent in their timing.

The second aspect apparent from Figure 4.9 concerns the difference between the rural and the two urban plots. The difference becomes most evident after the 10% mark and continues to the 98% mark, where the rural points constantly express lower discharge values than all the urban points. The rural plot expresses a low constant rate of increase in the lower discharges, up until the value of 0.5 cfs/sq.ml. This low rate is in contrast to the higher rate of the urban plots. As a result, higher discharges occurred in the urban catchments than in the rural, for the majority of the study period. However, at the lower discharge extreme of Figure 4.9, the final two recordings from the Highland Creek indicate lower values than those from the rural Cold Creek. The corresponding values from the Little Don catchment approximate very closely those values from the Cold Creek. Thus the difference between the urban and rural streamflows at this level is very small. Indeed a reverse situation, the flows from the rural catchment being larger than the flows from the Highland Creek, is experienced.
### TABLE 4.7

**A COMPARISON OF THE MEDIAN, THE UPPER QUARTILE, AND THE LOWER QUARTILE DISCHARGES EXTRACTED FROM THE DATA PRODUCED BY THE FLOW DURATION ANALYSIS.**

<table>
<thead>
<tr>
<th></th>
<th>LOWER QUARTILE (75%)</th>
<th>MEDIAN VALUE (50%)</th>
<th>UPPER QUARTILE (25%)</th>
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**RATIO OF URBAN TO RURAL DISCHARGES**

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<th></th>
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<tr>
<td>Little Don</td>
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</table>

Table 4.7 emphasises the difference between the urban and rural catchments by presenting certain discharges determined from the flow duration data. It also indicates the ratio of the urban to rural discharge for those discharges. The similarity between the values from the two urban catchments is apparent here, being rather surprising in that there is a substantial difference between the amount of imperviousness within each catchment. The greatest difference is in fact, in the median value where the Highland Creek records 0.72 cfs./sq.ml. and the Little Don
records a lower value of 0.67 cfs./sq.ml. However, the consistently lower values of the rural discharges substantiate the conclusions from the previous analysis; that the lower monthly discharges, concentrated in the summer and winter, are greater in the urban catchments.

The extent of this difference is indicated by the ratio of the urban to rural discharges for the percentiles listed in Table 4.7. These show that the greatest difference between the urban and rural discharges occurs at the median value, where the Highland Creek and the Little Don express a 64% and a 52% increase over the Cold Creek median value respectively. The upper and lower quartiles experience lesser differences but still indicate that the urban discharges are at least 43% greater than the respective rural discharge. Consequently, Figure 4.9 and Table 4.7 illustrate that the urban catchments experienced greater discharges than the rural catchment for the majority of the study period.

In an attempt to determine exactly at which times of the year the flows in the urban catchments are greater than those in the rural catchment, the flow duration data was plotted on logarithmic - probability scales, (see Figure 4.10). This facilitated the division of discharge into 'high', 'medium', and 'low' flow categories.
FIGURE 4.10

SOME OF THE POINTS OF THE FLOW DURATION 'CURVES' PLOTTED ON
LOGARITHMIC - PROBABILITY SCALES

- 'HIGH' FLOWS
- 'MEDIUM' FLOWS
- 'LOW' FLOWS

- THE HIGHLAND CREEK (urban)
- THE LITTLE DON (urban)
- THE COLD CREEK (rural)

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The boundaries were considered in terms of separating the higher discharges from the lower and to give an indication of the difference between the urban and rural discharges in the lower discharge range. Therefore, where the rural 'curve' converged on the urban 'curves', simplified to an 'average' trend by a single line, provided the boundary between the 'high' and 'medium' categories.

A least squares evaluation, performed to approximate the rural discharge values as a straight line, employed the uppermost 15 points from Figure 4.10. These were selected because they expressed a much greater slope than the lower points. The equivalent evaluation to approximate the urban flow duration 'curves' employed 23 uppermost points from both urban plots. These points covered the same percentage of time, indicated on the x-axis, as those points used to approximate the upper slope of the rural flow duration 'curve'. The convergence occurred at the 2.55 cfs./sq.ml. discharge and this established the upper boundary.

Another least squares evaluation, performed to approximate the lower portion of the rural flow duration 'curve', used the 15 lowest points and resulted in a straight line of lesser slope than that from the upper points. A distinct break of slope occurred where these two approximations converged and this was used as the second boundary, that between the 'medium' and 'low' discharge.
categories. Thus, monthly flows of less than 0.48 cfs/sq.ml. contributed to the 'low' flow category; flows between 0.48 and 2.55 cfs/sq.ml. were included in the 'medium' flow category; and flows greater than 2.55 cfs/sq.ml. were 'high' flows.

The occurrence of monthly flows within each category for the shortest continuous record (Highland Creek, from Oct. 1964 to Dec. 1973) are presented in Table 4.8. The table indicates that high flows only occurred during March and April. Evidently, the spring snowmelt contributed to the runoff of these months, so they were grouped together as the 'snowmelt' period. The months from May to October were combined as the 'summer' period because the snowfall records indicated that up until November the monthly snowfall totals were insignificant. Consequently, November to February, a period of snowfall, was classified as 'winter'.

The occurrence of monthly flows, recorded in Table 4.8, were summed up for these different periods and presented in bar graph form, (see Figure 4.11). It indicates the number of monthly flows of a given category occurring in each catchment and within each particular period.

Considering the snowmelt period, there is a close similarity in the occurrence of flows from each catchment. In fact, the Little Don catchment recorded less 'high' flows than the rural Cold Creek.
### Table 4.8

The occurrence of flows within each category for the period from Oct. 1964 to Dec. 1973

<table>
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<tr>
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FIGURE 4.11
THE OCCURRENCE OF MONTHLY FLOWS WITHIN DIFFERENT PERIODS OF THE YEAR.

Snowmelt Period

Summer Period

Winter Period

HC - Highland Creek
LD - Little Den
CC - Cold Creek

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However, only the Cold Creek catchment recorded a single 'low' flow occurrence during the snowmelt period, the remaining flows all being contained within the 'high' and 'medium' categories.

The summer period shows a marked difference from the snowmelt, in that the occurrence of 'medium' flows in the urban catchments is much greater than the occurrence in the rural. The converse is expressed in the 'low' flow category where 49 such flows occurred in the rural catchment compared to 16 and 20 flows in the Highland Creek and the Little Don catchments respectively. A similar situation is indicated in the winter period where 34 'medium' flows occurred in both urban catchments compared with only 18 in the rural. However, it is noticeable that in both the urban and the rural catchments the actual occurrence of 'medium' flows rather than 'low' flows is greater in the winter period.

The relative concentration of 'low' flows, in the summer period, found in all the catchments, can be explained by high summer temperatures which would raise the evapotranspiration rate and thereby reduce the amount of runoff. In the rural catchment, however, groundwater probably comprises a very large proportion of the total runoff, because summer precipitation would be mostly absorbed by the catchment or evaporated by the high temperatures, which in turn drastically reduces the
contribution of storm runoff. The result of this is an overwhelming dominance of 'low' flows.

On the other hand, in the urban catchments, summer precipitation is rapidly removed from the impervious surfaces as storm runoff, thus augmenting the streamflow. In the Literature Review Hollis (1975) suggests storm runoff can be generated from small and moderate precipitation events, so that the aggregated effect of this storm runoff is to increase the incidence of 'medium' flows in the urban catchments.

In the winter period, the greater occurrence of 'medium' flows in the urban catchments compared to the rural, could be an indirect result of the 'heat island' effect produced by cities, such as Toronto. The warmer temperatures within the city may help to melt the snow thereby increasing the amount of winter runoff. Concrete and asphalt surfaces appear to maintain snowcover to a much lesser extent than most vegetated surfaces. This, along with the removal of snow and the application of salt which acts as a catalyst to the snowmelting process, would certainly promote winter runoff compared to the rural situation.

To summarise these results, differences between the urban and rural streamflow records are concentrated in the lower range of flows, expressed as 'medium' and 'low' flows. The summer period showed a concentration of 'low' flows in
both the urban and rural catchments. However, the concentration was much greater in the rural catchment, in which 'low' flows occurred for 87% of the time compared with 38% and 40% of the time in the Highland Creek and Little Don catchments respectively. The increasing occurrence of 'medium' flows in the winter period compared to the summer, a feature evident in all the catchments, appeared to be slightly more extreme in the urban catchments.

Consequently, urbanisation appears to have increased those flows that occurred over the greater part of the study period. That increase in flow varied slightly as the discharge increased; the ratio of urban to rural flow aspiring to a value of 1.64 between the Highland Creek and the Cold Creek median discharges. The increase in discharge recorded in the urban catchments was also concentrated in the summer and winter periods, when the tendency was for rural 'low' flows to be replaced by 'medium' flows in the urban catchments. This tendency was also slightly greater in the winter period rather than the summer.
5. CONCLUSIONS.

The examination of monthly streamflow data from two urban catchments in comparison with the corresponding streamflow record from a nearby rural catchment indicated that urbanisation affects both the amount and the occurrence of those flows throughout the year. The major difference caused by urbanisation was the increase in discharges that were recorded over most of the study period. These increases occurred in most of the 'medium' and 'low' flows; those flows of lesser magnitude. The extent of the increase appeared to be greatest between flows that were equalled or exceeded from 50% to 20% of the study period; that is, the greatest differences occurred within the magnitude of most of the 'medium' flows. The value of these flows ranged from 0.67 to 1.25 cfs./sq.ml. in the urban catchments and from 0.44 to 0.85 cfs./sq.ml. in the rural catchment.

These increases appear to have occurred throughout the summer and winter periods of the year. In the summer period the overwhelming dominance of 'low' flows in the rural catchment has been replaced to a certain extent, by increased discharges in that there is a greater incidence of 'medium' flows. Similarly, in the winter period there is a greater incidence of 'medium' flows in the urban catchments compared with the rural catchment.
During this same time there has also been a greater variability of flow in the urban catchments. In the rural catchment the consistently 'low' flows are followed by gradually increasing flows during the winter. In the urban catchments increased flows occur during the summer as well as the winter. This variability prompts two lines of consideration.

First, the urban catchments may indicate an increased dependence on storm runoff compared to the rural catchment. This is more likely to be the case during the summer when the streamflow from the rural catchment would be expected to be largely comprised of groundwater. In the urban catchments summer precipitation can be rapidly removed from the impervious surfaces and thereby contribute to an increase in streamflow. The precipitation falling on the rural catchment, however, would tend to be evaporated or infiltrated into a storage of some form.

The second consideration could be described as a partial breakdown in the seasonality of flow. The high snowmelt flows in spring are consistently followed by low summer and slightly increased winter flows in the rural catchment. In the urban catchments for the summer and winter periods this general sequence is replaced by a greater variation in the magnitude of consecutive flows. This is the result of interference by urbanisation with the climatic controls that
are normally exerted upon the streamflow regimen in rural areas.

However, the major seasonal component of the streamflow records, the high spring snowmelt flows, accompanied throughout the remainder of the year by much lower flows, remains largely unaltered in the urban catchments. The urban time series graphs indicate snowmelt flows was approximately the same values as those in the rural catchment. However, the slightly different shape of these snowmelt peaks suggests that the timing of the snowmelt flows may be altered. In the urban catchments the widening of these peaks to include both the month of March and April suggested that the snowmelt period traversed the end of March and the beginning of April, whereas in the rural time series the snowmelt period usually occurred within a single month.

The increase in the lower discharges is found to be in agreement with the results of the studies discussed in the Literature Review. However, the majority of these studies employed data from individual rainfall - runoff events to indicate that runoff yields are increased. The results from this study indicate that this effect is still apparent over a combination of storm and subsequent dry periods in that a monthly database was employed. It also indicates that the effect can still be detected using a smoothed figure, that
being a mean value, which has been averaged over the continuous period of one month. Thus, the increased storm runoff in the urban catchments more than compensates for the intervening recession or "dry" periods because the monthly precipitation totals over all the catchments were proven to be no different from each other. This is, however, somewhat surprising as there is a body of literature that confirms the effect of urbanisation on precipitation. For example, Huff & Changnon (1972) found that in examining monthly and seasonal precipitation records within and around St. Louis, "a localised increase in total seasonal precipitation was found in all seasons, but was strongest in summer," (p.840). This difference was even greater when short duration storms, for example convective thunderstorms, were analysed. Huff (1975) showed that a substantially greater water yield from urban affected cells (storm units) compared with that from the rural (control) cells. However, these results are indicative of a particular climate, that of the Midwest of USA; a climate that is dominated by thunderstorm precipitation. Within Southern Ontario thunderstorm activity may not play such an important role in the total production of precipitation as in the Midwest. Storms of lesser intensity and of more moderate properties may contribute to the majority of the total precipitation and as such may not be as affected by urban areas.
However, the examination of the monthly precipitation totals indicated that the amount of precipitation, and therefore the amount of moisture generally available for runoff, was no different between the catchments during the study period. Therefore, the presence of urbanisation within the Highland Creek and the Little Don catchments has increased the monthly streamflow from essentially the same amount of precipitation.
FOOTNOTES.

1. A variable is defined by Freeze (1974) as a characteristic of the system that can be measured and that assumes different numerical values at different times.

2. The term Recurrence Interval (also called the Return Period) is the time which, on average, elapses between two events which equal or exceed a particular level. So, the N-yr. event, the event which is expected to be equalled or exceeded, on average, every N years, has a recurrence interval of N years, (Wilson, 1969).

3. A 'natural' area or basin is one that has not experienced any land-use changes caused specifically by the encroachment of urbanisation. It therefore, sustains either a rural, agricultural, vegetated or completely natural land cover and typifies a pre-urban or non-urban condition. Conversely, an urban basin is one which contains some recognisable form of urbanisation, usually indicated by built-up areas or agglomerations of impervious surfaces of asphalt and concrete.

4. The centroid of a precipitation event can be defined as the time when half of the rainfall volume has already fallen and the remaining half has yet to fall.

5. Carter (1961) describes a "partially sewered" basin as containing virtually complete suburban development, with a low imperviousness of slightly greater than 10%, and a partly sewered drainage system in which the principal stream channels are maintained in their natural condition.
6. The factors analysed by Hollis & Luckett (1976) included:
   a) the area of the catchment;
   b) the percentage of area covered by impervious urban surfaces;
   c) the percentage of area covered by woodland;
   d) the Relief Ratio, \((R_n)\);
   e) the form factor, \((R_f)\);
   f) the main stream slope factor.
Using these variables Hollis & Luckett were able to determine the influence of land-use variables on the channel cross-section ratio, while controlling those morphometric factors.

7. The modal flow is described by Searcy (1959) as an appropriate 'normal' flow. It is defined as the point of inflection of a flow duration curve when plotted on rectangular co-ordinates and using the cumulative frequency of discharge.

8. After inquiring about the exact nature of the procedure that William Graf used in his study to measure his urban parameter, he replied that, "photo-derived maps were drawn from the air photo base data. These maps were then planimetered." This is quoted from a personnel communication with Prof. W. Graf., dated 24th November 1976.

9. In response to my written inquiry on the exact nature of the sampling procedure used in his 1974 study of Canon's Brook, Dr. G. Hollis replied, in a letter dated 24/11/76, "In the air photo work I used a stratified random un-aligned dot sampling method."

10. In response to my inquiry concerning the measurement of urban parameters, Prof. Colin Taylor replied, "To do this we took a large scale map into the field and marked in pavements, driveways, parking lots, buildings and the streets themselves (basically all non-vegetated areas). These were then measured using a planimeter." This is quoted from a letter dated 25/5/76.

11. The data for the meteorological stations was sent, on request, by Mr. D.N. McMullen, from the Conservation Authorities Branch of the Ministry of Natural Resources. He sent a photocopy of the relevant section (p.189-192) of "Meteorological Observations in Canada", published by Environment Canada.
12. On page x, within the notes headed 'Explanation of Reference Index Pulications', in the Index itself, the type of flow is indicated as 'NAT', "where the flow is known to be natural," that is, it is not artificially regulated. The variation in flow was the result of natural fluctuations in the precipitation - runoff relation. All the catchments in the study were referenced in the 1975 Index as 'NAT'.

13. In all the analyses the monthly streamflow value was measured in cubic feet per second per square mile, and this was abbreviated to cfs/sq.ml.

14. The abbreviation 'cumecs' is a measure of discharge, in the units cubic metres per second.
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APPENDIX 1

SUMMARY OF LAG TIME DEFINITIONS,
(modified from Esprey, Morgan, & Masch, 1966).

T1 = Time from beginning of rainfall to the centroid of runoff, (Linsley, Kohler, & Paulus, 1958).

T2 = Time from the centre of mass of rainfall excess to the peak discharge, (Eagleson, 1962).

T3 = Time from centre of mass of rainfall excess to the centre of mass of the runoff, (Martens, 1968).

T4 = Time from the centroid of rainfall to centroid of runoff, (Carter, 1961).

T5 = Time from the beginning of the rainfall to the peak discharge,

T6 = Time from cessation of effective rainfall to the inflection point of the recession side of the resulting runoff hydrograph, T6 = Tc, (Snyder, 1958).

T7 = Time from the centroid of rainfall to the peak discharge.

Tr = Time required for the water in the channel at the gauging station to rise from the low to the maximum stage, (Esprey, Morgan, & Masch, 1965).

Tc = Time required for a drop of water to travel from the most remote point in the watershed to the gauging station.
APPENDIX 2

THE DETAILED CALCULATIONS OF APPLYING THE WILCOXAN TEST TO THE STREAMFLOW RECORDS FROM EACH OF THE URBAN AND THE RURAL CATCHMENT.

1. THE HIGHLAND CREEK AND THE COLD CREEK STREAMFLOW RECORDS

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<th>(B) MEAN MONTHLY DISCHARGE (CFS/SQ.ML.) OF COLD CREEK</th>
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TOTALS:  902   5,310

No pairs omitted
Thus, N = 111.

\[ Z = \frac{902 - \frac{1}{4} (111 \times 112)}{\sqrt{111 \times 112 \times 223}^{2/4}} \]

\[ = \frac{-2206}{339.873} \]

\[ = -6.491 \]

N.B. The total Highland Creek record, from Oct. 1964 to Dec. 1973, was compared to the corresponding months of the Cold Creek record.
## 2. THE LITTLE DON AND THE COLD CREEK STREAMFLOW RECORDS.

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**Appendices** 193
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0.77 0.47 0.30 87.5
0.63 0.37 0.26 74
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0.67 0.30 0.37 94
0.84 0.40 0.44 99
1.12 0.48 0.64 111
1.32 0.56 0.76 114
1.25 0.98 0.27 75
1.10 0.89 0.21 63.5
3.10 2.93 0.17 51.5
1.72 1.26 0.46 101
1.08 0.76 0.32 91
0.74 0.45 0.29 82
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0.53 0.39 0.14 41.5
0.50 0.35 0.15 46
0.74 0.45 0.29 82
1.11 0.60 0.51 104
0.92 0.45 0.47 103
1.66 0.78 0.88 117.5
1.03 0.65 0.38 96
1.91 2.50 -0.59 108
1.85 1.31 0.54 105
1.81 0.83 0.98 119
0.94 0.39 0.55 106.5
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0.50 0.33 0.17 51.5
0.41 0.41 0.0 65.5
0.71 0.47 0.24 71.5
0.56 0.38 0.18 56.5

Two pairs were omitted
Thus N = 121.

\[
Z = \frac{764.5 - \frac{1}{4}(121 \times 122)}{\sqrt{\frac{121 \times 122 \times 243}{24}}} \\
= \frac{-2926}{386.607} \\
= -7.568
\]
N.B. The total streamflow record for the Little Don catchment, Oct. 1964 to Dec. 1974, was compared with the corresponding months from the Cold Creek catchment.
APPENDIX 3

A LISTING OF PROGRAM 'SMOOTH', WHICH CALCULATED THE SMOOTHED SEQUENCES FROM THE ORIGINAL DATA.

C PROGRAM 5.6 FROM DAVIS, J.C.
C FOR TERMINAL USE SET F:9/NUMBERS;IN AND SET F:6 ME
C FOR LP OUTPUT SET F:9/NUMBERS;IN AND SET F:6 LP
C EXECUTE UNDER FORTRAN
C FOR OPTIONS ENTER: BC, NS
C OR SIMPLY DO A START RICHLMN AFTER SETTING DCB'S
C
C ROUTINE SMOOTH
C ROUTINE TO PERFORM M TERM SMOOTHING
A MAXIMUM NUMBER OF DATA ENTRIES OF 250
C
C XIN IS DATA SEQUENCE OF LENGTH N TO BE SMOOTHED BY
M-TERM MOVING AVERAGE, LENGTH OF OUTPUT IS IE=N-M+1
SMOOTHED SEQUENCE IS XOUT
XOUT(I)=THE SMOOTHED ESTIMATE FOR XIN(I+(M-1)/2)
M MUST BE A ODD NUMBER
C
C DIMENSION XIN(250), XOUT(250)
C
C READ IN THE NUMBER OF TERMS TO BE USED IN THE MOVING AVERAGE
C
90 WRITE(6,70)
70 FORMAT(/'ENTER THE SMOOTHING VALUE',/,'THE VALUE MUST BE ODD.'
INPUT M
Z=AMOD(FLOAT(M),2.)
IF (Z.EQ.0) GO TO 90
WRITE(6,71)
71 FORMAT(/'ENTER THE NUMBER OF DATA ENTRIES'/)
INPUT N
C
READ IN THE DATA SEQUENCE TO BE SMOOTHED AND PRINT IT OUT
CALL READM(XIN,N,NM,250,250)
CALL PRINTM(XIN,N,1,250,1)
IE=N-M+1
DO 100 I=1, IE

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SUM=0.0
DO 101 J=1,M
   K=I+J-1
   SUM=SUM + XIN(K)
101 CONTINUE
   XOUT(I)=SUM/FLOAT(M)
100 CONTINUE
C
C PRINT OUT THE SMOOTHED DATA SEQUENCE
C
WRITE(6,2001)
2001 FORMAT(//' SMOOTHED DATA SEQUENCE')
   CALL PRINTM(XOUT, IE, 1,250,1)
SY=0.0
SYY=0.0
DO 102 I=1,N
   SY=SY+XIN(I)
   SYY=SYY+XIN(I)**2
102 CONTINUE
SYS=0.0
SYYS=0.0
SYC=0.0
SYYC=0.0
SSD=0.0
DO 103 I=1,IE
   J=I+M/2
   SYS=SYS+XIN(J)
   SYYS=SYYS+XIN(J)**2
   SYC=SYC+XOUT(I)
   SYYC=SYYC+XOUT(I)**2
   SSD=SSD+(XIN(J)-XOUT(I))**2
103 CONTINUE
SSO=SYY-SY*SY/FLOAT(N)
SSOS=SYYS-SYS*SYS/FLOAT(IE)
SSS=SYYC-SYC*SYC/FLOAT(IE)
PSS=(SSS/SSOS)*100.0
WRITE(6,1000)
WRITE(6,1001) SSO
WRITE(6,1002) SSOS
WRITE(6,1003) SSS
WRITE(6,1004) SSD
WRITE(6,1005) PSS
ITYPE = 3
   CALL TSPLOT (XOUT,IE,ITYPE)
STOP
1000 FORMAT(I3)
1001 FORMAT(36H1SUMS OF SQUARES OF ORIGINAL DATA = ,F20.8)
1002 FORMAT(36H1SUMS OF SQUARES OF TRUNCATED DATA = ,F20.8)
1003 FORMAT(36H1SUMS OF SQUARES OF SMOOTHED DATA = ,F20.8)
1004 FORMAT(36H1SUMS OF SQUARES DUE TO DEVIATION = ,F20.8)
1005 FORMAT(21H1% GOODNESS OF FIT = ,F20.8//)
END

PROGRAM 4.1

SUBROUTINE TO READ A MATRIX
HAVING N ROWS AND M COLUMNS

SUBROUTINE READM(A,N,M,N1,M1)
DIMENSION A(N1)

READ SIZE OF THE MATRIX

READ MATRIX ONE ROW AT A TIME
READ(9,1001,END=2000)(A(I),I=1,N)

CONTINUE

WRITE(6,5000)

RETURN

END

PROGRAM 4.2

SUBROUTINE TO PRINT A MATRIX
HAVING N ROWS AND M COLUMNS

SUBROUTINE PRINTM(A,N,M,N1,M1)
DIMENSION A(N1,M1)

PRINT MATRIX OUT IN STRIPS OF 10 COLUMNS

DO 100 IB=1,M,10
   IE=IB+9
   IF(IE=M) 2,2,1
   IE=M

PRINT HEADING

WRITE(6,2000) (I,I=IB,IE)

DO 101 J=1, N

PRINT ROW OF MATRIX

WRITE(6,2001) J,(A(J,K),K=IB,IE)

CONTINUE

CONTINUE

RETURN

FORMAT(1X,10I12)

FORMAT(1H0,I3,')',10F12.4)

END

PROGRAM 5.7
C TO PLOT 1-DIMENSIONAL DATA ON THE LINE PRINTER
C
SUBROUTINE TSPLOT(X,N,ITYPE)
C
C X IS THE ONE DIMENSIONAL ARRAY TO BE PLOTTED
C N IS THE NUMBER OF ELEMENTS IN X THAT ARE TO BE PLOTTED
C
C IF ITYPE=1, THE DATA TO BE PLOTTED WILL HAVE THE RANGE (-1,1)
C IF ITYPE=2, ANY DATA MAY BE PLOTTED
C IF ITYPE=3, LOG10 OF THE X ARRAY WILL BE PLOTTED,
C THE ORIGINAL X ARRAY WILL NOT BE DESTROYED
C
C
DIMENSION X(120),IOUT(61),XX(13)
DATA II,ISTAR,IBLNK/'I','*',' '/
IF(ITYPE.NE.1) GO TO 11
XMIN=-1.0
XMAX=+1.0
GO TO 12
11 XMIN=X(1)
XMAX=XMIN
DO 100 I=1,N
IF (X(I).LT.XMIN) XMIN=X(I)
IF (X(I).GT.XMAX) XMAX=X(I)
100 CONTINUE
IFQTYPE.NE.3) GO TO 12
XMIN=ALOG10(XMIN)
XMAX=ALOG10(XMAX)
12 DX=XMAX-XMIN
XXX=XMIN
DO 101 1=1, 13
XX(I)=XXX
IFQTYPE.EQ.3) XX (I ) = 1 0. 0**XXX
XXX=XXX+DX/12.0
101 CONTINUE
WRITE(6,2004)
WRITE(6,2000) (XX(I),I=2,12,2)
WRITE(6,2002)
WRITE(6,2001) (XX(I),I=1,13,2)
DO 102 I=1,N
DO 103 J=1,61
IOUT(J)=IBLNK
103 CONTINUE
DO 104 J=1,61,10
IOUT(J)=II
104 CONTINUE
XXX=X(I)
IFQTYPE.EQ.3) XXX=ALOG10(XXX)
IX=IFIX((XXX-XMIN)*60.0/DX)+1
IOUT(IX)=ISTAR
WRITE(6,2003) X(I),IOUT

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CONTINUE
WRITE(6,2002)
WRITE(6,2001) (XX(I),I=1,13,2)
WRITE(6,2000) (XX(I),I=2,12,2)
RETURN
2000 FORMAT(11X,6F10.4)
2001 FORMAT(6X,7F10.4)
2002 FORMAT(11X,'+',12('+-++'))
2003 FORMAT(1X,F10.4,61A1)
2004 FORMAT(1H1)
STOP
END
APPENDIX 4

AN EXAMPLE OF THE OUTPUT PRODUCED BY 'SMOOTH'

THE 49 TERM SMOOTHING OF THE COLD CREEK STREAMFLOW RECORD

After the printout of the input data sequence, the smoothed sequence is printed out in the form illustrated below, followed by a graph, automatically scaled to fit onto the printer, is printed out.

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Appendices 204
APPENDIX 5

A LISTING OF PROGRAM 'FLOWDUR', WHICH CALCULATED DATA
FOR THE FLOW DURATION ANALYSIS.

C TO RUN THIS PROGRAM....
C SET F:6 TO ME OR LP WHICHEVER OUTPUT YOU PREFER
C SET F:5/FILENAME;IN WHERE FILENAME IS THE NAME
C OF YOUR DATA FILE.
C THEN EXECUTE UNDER FORT4 OR SIMPLY DO START SORTLMN.
C
C A MAXIMUM OF 250 DATA POINTS CAN BE USED
C
DIMENSION X(250),A(250)
OUTPUT 'ENTER THE NUMBER OF DATA'
INPUT M
DO 7 I=1,M
READ(5,5)X(I)
5 FORMAT(F8.3)
A(I)=X(I)
7 CONTINUE
DO 1 I=1,M
LIMUP=M-I
DO 2 J=1,LIMUP
IF(X(J).LT.X(J+1)) GO TO 3
GO TO 2
3 TEMP=X(J)
X(J)=X(J+1)
X(J+1)=TEMP
2 CONTINUE
1 CONTINUE
WRITE(6,9)M
9 FORMAT(1,' THE NUMBER OF DATA ENTRIES IS 'I3//)
WRITE(6,8)
8 FORMAT(8X,'INPUT DATA'5X' RANKED DATA'/)
WRITE(6,4)(I,A(I),X(I),I=1,M)
4 FORMAT(1X,I3,')',4X,F7.3,9X,F7.3)
ITYPE=2
CALL TSPL0T(X,M,ITYPE)
END

C PROGRAM TO PLOT 1-DIMENSIONAL DATA ON THE LP
C SEE PROG. SMOOTH OR AVER FOR THE DETAILS
SUBROUTINE TSPL0T(X,N,ITYPE)

DIMENSION X (250),IOUT(61),XX(13)
DATA II,ISTAR,IBLNK/'I','**','/'
IF(IATYPE.NE.1) GO TO 11
XMIN=-1.0
XMAX=+1.0
GO TO 12
11 XMIN=X(1)
XMAX=XMIN
DO 100 I=1,N
IF (X(I).LT.XMIN) XMIN=X(I)
IF (X(I).GT.XMAX) XMAX=X(I)
100 CONTINUE
IF(IATYPE.NE.3) GO TO 12
XMIN=ALOG10(XMIN)
XMAX=ALOG10(XMAX)
12 DX=XMAX-XMIN
XXX=XMIN
DO 101 I=1, 13
XX(I)=XXX
IF(IATYPE.EQ.3) XX (I )= 1 0.0**XXX
XXX=XXX+DX/12.0
101 CONTINUE
WRITE(6,2004)
WRITE(6,2000) (XX(I),I=2,12,2)
WRITE(6,2002)
WRITE(6,2001) (XX(I),I=1,13,2)
DO 102 I=1,N
DO 103 J=1,61
IOUT(J)=IBLNK
103 CONTINUE
 DO 104 J=1,61,10
IOUT(J)=II
104 CONTINUE
XXX=X(I)
IF(IATYPE.EQ.3) XXX=ALOG10(XXX)
IX=IFIX((XXX-XMIN)*60.0/DX)+1
IOUT(IX)=ISTAR
WRITE(6,2003) X(I),IOUT
102 CONTINUE
WRITE(6,2002)
WRITE(6,2001) (XX(I),I=1,13,2)
WRITE(6,2000) (XX(I),I=2,12,2)
RETURN
2000 FORMAT(11X,6F10.4)
2001 FORMAT(6X,7F10.4)
2002 FORMAT(11X,'+',12('-----+'))
2003 FORMAT(1X,F10.4,61A1)
2004 FORMAT(1H1)
STOP
END
APPENDIX 6

AN EXAMPLE OF THE OUTPUT PRODUCED BY 'FLOWDUR'

THE FLOW DURATION CALCULATION FOR THE HIGHLAND CREEK RECORD

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Appendices 209
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Appendices 211
## APPENDIX 7

The detailed calculations of applying the Wilcoxon test to the monthly rainfall and precipitation totals from each of the urban and the rural catchment.

1. The monthly rainfall totals from the Ellesmere (Highland Creek) and the Cold Creek (Cold Creek) meteorological stations.

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\]

N.B. The monthly rainfall totals for the study period Oct. 1964 to Dec. 1974, were tested wherever corresponding monthly records from both meteorological stations could be matched.
2. THE MONTHLY PRECIPITATION TOTALS FROM THE RICHMOND HILL OWRC (LITTLE DON) AND THE COLD CREEK (COLD CREEK) METEOROLOGICAL STATIONS.

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**TOTALS:** 2,678 3,650

One pair omitted

Thus \( N = 112 \).

\[
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\]

N.B. Same conditions apply to this analysis as in the previous one in regard to the records tested.
APPENDIX 8

DATA COMPRISING THE 13 TERM SMOOTHED SEQUENCES FOR THE STUDY CATCHMENTS.

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N.B. The 13 term smoothed sequences covered the period April 1965, (Pt.1) to June 1974, (Pt.111).
APPENDIX 9

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N.B. The 49 term smoothed sequences covered the period from October 1966, (Pt.1) to December 1972, (Pt.75).
APPENDIX 10

DATA COMPRISING THE FLOW DURATION 'CURVES' FOR THE THREE CATCHMENTS.

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Appendices 225