STORMWATER MANAGEMENT:

Emerging Planning Approaches
and
Control Technologies

Chapter 5

" HYDROLOGIC SYSTEMS "

CHAPTER 5

5.1 INTRODUCTION

5.1.1 Training Objectives

The objectives of this module are:

- to provide an overview of the physical conditions which are addressed in the analysis of hydrologic systems,

- to describe the basic elements of the analysis of rainfall runoff processes

The application of hydrology to problems of engineering interest is the focus of Chapter 1 and is not addressed in detail in this module.

5.1.2 Background

Hydrology is a discipline which deals with the movement of water through our environment. Although the basic principles which govern this are readily understood, the details of the processes involved can be very complex. This arises from the tremendous amount of detail which is required if hydrologic processes are to be fully described. It is obvious that water falls from the sky, and then along or through the ground, and it is generally obvious what the major routes for flow must be. However, translating this into a detailed assessment of the hydrologic process requires that one deals with such things as:

- the random variability of rainfall,
- the routing of flows through a complex network of overland channels and surfaces,
- the physics which govern infiltration and movement of water in a soil,
- the biological response to rainfall, including evapotranspiration,

and so on. This amounts to a problem which is not simple at all.

Since this is so, the science of hydrology has evolved into a practice that relies heavily on empirical relationships or concepts, that describe the major hydrologic process in a relatively gross way. Statistical and probabilistic methods are often employed to deal with uncertainty. Aside from this, there are a number of very complex and comprehensive models (that still only represent a small fraction of reality) which have been developed to describe parts of the hydrologic process that have become of interest in more detail. This leaves the hydrologist with what amounts to an art as much as a science. The present best state of the art in this field still relies heavily on the use of judgement of the practitioner to balance the complex reality with the need for useful simplifications.

5.2 BASIC HYDROLOGY

5.2.1 The Hydrologic Cycle

The hydrologic cycle is fundamental to the study of hydrology. The cycle involves movement of water through the environment. A simple illustration of the hydrologic cycle is presented graphically in Figure 5-1.

1. Water evaporates from water bodies, or is emitted through transpiration from plants, or is otherwise sent to the atmosphere.

2. The resulting water vapor is transported by air movement.

3. The vapour condenses and forms clouds, and eventually falls as precipitation.

4. Water collects and travels through the land:

   - on the land surface, it can travel overland to defined drainage routes and hence to surface water bodies, or to groundwater recharge elsewhere,

   - if it infiltrates into the ground, it may be emitted through evapotranspiration or may emerge from the groundwater system into lakes or rivers.

Of course, other factors can affect this gross picture. In particular, human activity can radically affect the movement of water through the environment. In fact, most practical applications of hydrology are intended to either i) modify the natural movement of water (as in flood control), or ii) mitigate changes to the hydrologic system that human activity has caused (as in stormwater management).

5.2.2 The Rainfall-Runoff Process

Generally, hydrology in Civil Engineering practice focuses on the part of the cycle that deals with the transformation of rain into runoff as it hits the ground. The movement of that water through channels and reservoirs is assessed as an important part of that analysis. An interest in the recharge and movement of water in the ground has more recently emerged as an important consideration. The areas of hydrology that respond to the surface components of flow can be generally grouped into rainfall-runoff processes and hydrologic routing analysis. Hydrologic routing is essentially the counterpart of the more general field of hydraulics, but developed into various accepted norms and practices that support the practice of hydrology.

To understand the models and tools which are used in the practice of hydrology, it is useful to consider the following three areas:

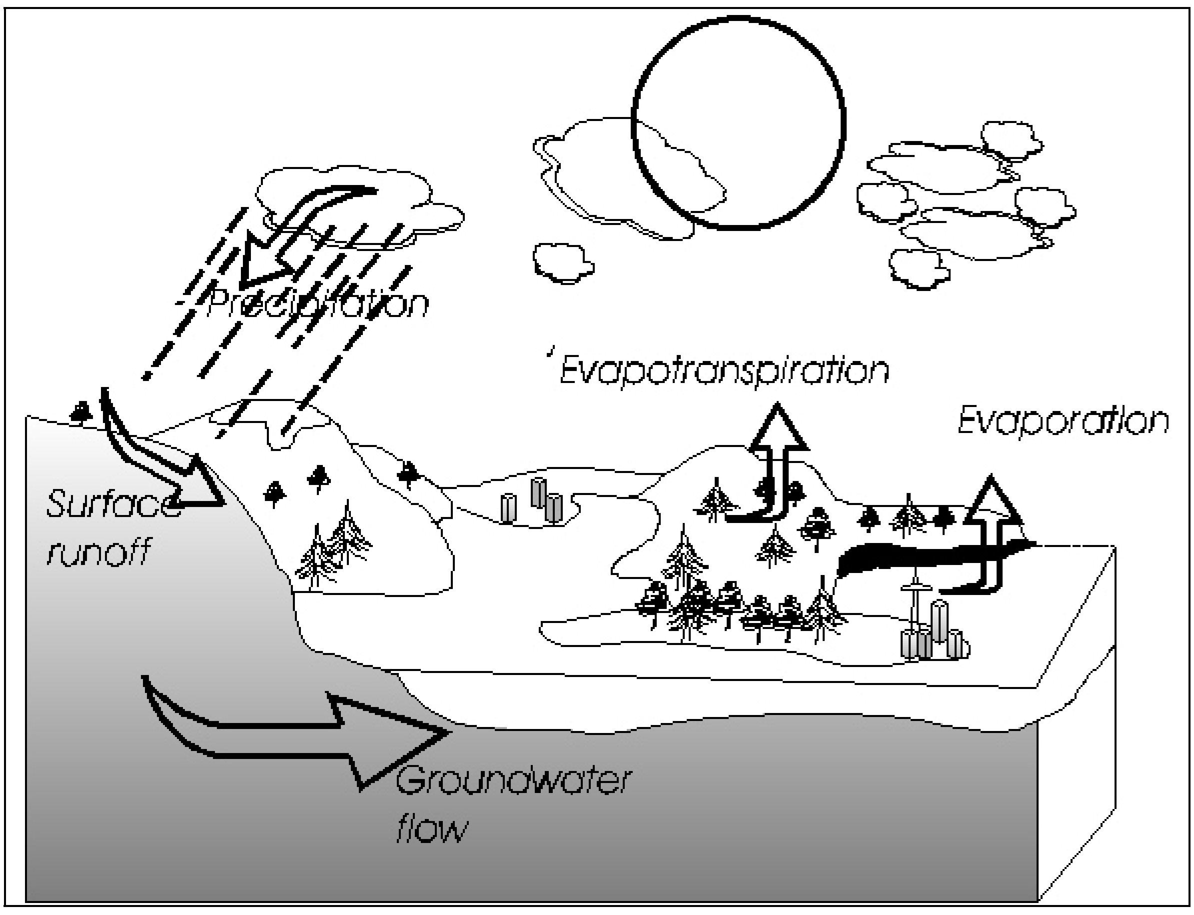

Figure 5-1 *Hydrologic cycle*

- Loss models, that deal with the amount of water that infiltrates into the ground as rainfall hits the land surface.

- Surface routing models, that deal with conversion of volumes of excess rain into a flow rate. Excess rain is that component of rain that is not lost to infiltration, evaporation, storage, or other factors, but is available to travel across and off the catchment surface.

- Hydrologic routing models, that deal with the movement of runoff in channels and other water bodies.

Some methods of analysis group part or all of these, while others deal with them separately.

When rain falls from the sky, it is usually conceived of as an 'event' which has a characteristic volume and duration, and a pattern of intensity. Some of that rainfall infiltrates into the ground, is retained in surface depression storage, or is otherwise lost; the remainder is 'excess rainfall'. That excess rainfall volume gives rise to a period of runoff. Plotted on a graph of flow rate vs time, the pattern of runoff from the catchment usually has a shape which starts low, peaks, and tails off; this pattern of runoff rate is known as a 'hydrograph'.

One of the reasons that the science of hydrology has achieved significant importance in engineering practice, is that urbanization has a major impact on the hydrologic cycle. This impact, and the means of dealing with it, are discussed in some detail in Chapter 1. In this Chapter, it is noted that the need to understand and predict the effects of development on rainfall and runoff, as well as other aspects of the interaction of humans and their environment, have had a significant impact on the tools developed for assessing problems in hydrology. This Chapter stresses tools and concepts most commonly used in the practice of hydrology in Ontario. An extensive literature deals with many other aspects of the problem.

5.3 RAINFALL-RUNOFF ANALYSIS

Most of the models used in engineering practice are deterministic in nature. That is, they attempt to represent rainfall runoff processes by making predictions based on physical principles and without direct treatment of the element of chance. Such models might be formulated with a great deal of detail, but might represent the system in a very simplified way; either way, they address cause and effect. There has been some attention to probabilistic or stochastic methods (which represent rainfall-runoff as a random process and approach the problem quite differently than the deterministic models do). However in general these have not received major attention in applied hydrology.

Probability in most cases is applied to the estimate of rainfall or runoff event frequency, and to some degree in the estimation of variability or error in model prediction. There are some advantages to probabilistic methods, in the speed and economy with which they can identify solutions and provide estimates of hydrologic performance. However, they as yet are not the major tool of choice in stormwater management for most practitioners in Ontario.

5.3.1 Basic Concepts in Analysis

Modelling Approach

Typically, flow rate is taken to be a continuous variable, which changes in some way from one instant to another. Rainfall, on the other hand, is typically taken to have a particular intensity over one time interval and a new intensity over the next time interval, with no transition between, and therefore has the form of a discrete variable.

In either case, a variable such as runoff rate or volume can be assessed to establish the probability of any particular value which that variable might take. This can be complex. For example, one might be interested in estimating how often one will experience a particular flow rate during a snow melt period. This specific flow rate will depend on the temperature, precipitation and snow pack depth. We assume that we know or can estimate the flow associated with any combination of temperature, precipitation, and snow pack depth. We then need to estimate how likely a particular flow rate is.

> *A Statistical Estimate* Statistical models might attempt to solve this problem by defining the individual probabilities of each variable, and the way in which those probabilities combine to provide a joint probability. Once this is done, one could i) identify all the combinations of precipitation, pack depth and temperature that produce a particular flow; ii) estimate the probability of each identified combination; and iii) add up the individual probabilities to arrive at a total probability for the flow rate.
>
> *A Continuous Simulation Estimate* Continuous simulation models attempt to overcome this problem in a rather different way. Such models could be used to i) complete a long term simulation of snow pack, temperature, and precipitation records, to generate a long term estimate of flow; ii) examine this long term simulation; and, iii) count the number of times that a particular flow rate was simulated to have occurred, which provides an estimate of the probability of that flow rate.
>
> *A Single Event Estimate* A compromise between the above methods is to produce flows for a particular design event condition. One could i) define a rainstorm event with a particular probability of occurrence, say, one in one hundred years, ii) simulate the result of that flow rate, and ii) consider that the simulated flow has a probability which matches that of the rainfall event, in this case a one in one hundred year frequency of occurrence. In fact, a flow derived this way has a somewhat tenuous relationship to a particular probability of flow, since the variations in catchment characteristics (soil moisture, etc.) are not accounted for in the estimate of probability. This may not necessarily be a serious problem in some situations. The need for a better estimate of probability is determined by the case at hand.

In the final analysis, it is the quality of the analysis that is important. All methods can be used to produce good or bad results. It is considered, however, that for a given level of accuracy, the effort involved in producing meaningful probabilities with continuous simulation is less than with the other methods, particularly if the physical system is complex.

5.3.2 Precipitation Analysis

Rainfall Hyetograph

Rain is usually measured in incremental volumes at gauging stations. These increments take the form of daily volume, or volume at some other increment of time. It is possible to plot the rainfall volume, or its equivalent the rainfall intensity, for incremental times during the event. The result is a plot known as a hyetograph. The shape of the hyetograph for a particular rainfall event constitutes the time history of that event.

A hyetograph can be used in single event and continuous simulation anlaysis of rainfall-runoff processes. A long-term continuous hyetograph consists of a series of rainfall pulses through time. To separate it into independent storm events, a definition of the minimum interevent time is required; the reason for this being so that any two pulses of rainfall can be considered to be belonging to separated events if the time period between the pulses is longer than the minimum interevent time. Storm event analysis can be used to determine the statistics and the probability distributions of rainfall volume, duration, average intensity, and interevent time from a long-term hyetograph. Analysis of a number of rainfall record across Canada indicates these characteristics can be described as exponential density functions. Such statistical information can be used in statistical analysis of reainfall-runoff process.

Rainfall Intensity-Duration-Frequency Curves

An observed hyetograph is useful as an indication of the severity or typical nature of rainfall events, and in calibration. However, a natural event often has little intuitive significance and no discernable probability, since there are no two events that are identical. It is therefore useful to seek alternatives to the direct use of observed rainfall events.

The most basic definition of a storm event lies in its duration and volume, and possibly in its peak intensity. In the long term, rainfall can be assessed according to the frequency at which a particular storm of a given duration and volume occurs. This relationship is defined by curves known as Intensity/ Duration/ Frequency (IDF) curves.

To generate an IDF curve, observed rainfall records are scanned for all instances of a particular combination of duration and volume; the number of times that combination occurs provides a measure of likelihood. Assessing the problem in terms of the number of times a combination is exceeded, provides a probability that expresses the frequency of exceedance of that combination. Compiling statistics for all combinations leads to curves that define the relationship between rainfall event intensity, duration, and frequency.

The Atmospheric Environmental Service (AES) defines an intensity-duration event for a particular duration, t_o, as the annual maximum intensity determined. The AES types IDF curves are derived by scanning the clocktime rainfall record with the event definition: $t <= t_o$, annual max

$\boldsymbol{i}=(\boldsymbol{v}/\boldsymbol{t_o})$. The extreme annual series is determined, and a Type 1 extreme value distribution is used to calculate the frequency of intensity and duration.

$$i = \frac{a}{(t + b)^c} \tag{5.1}$$

where:

i	=	intensity (in/hr) or (mm/hr)
t	=	time in minutes
a, b, c	=	constants developed for each IDF curve.

Once an IDF relationship is developed for the area of interest, a certain combination of design intensity and duration can be determined for a particular frquency of occurrance. The IDF curves are used extensively in single event analysis of rainfall-runoff processes.

Design Events

Synthetic design events are used to provide uniformity of approach. They usually represent an attempt to define a single event that has characteristics which represent the average of the many different real events of a particular size that occur in an area.

The design storm is based upon the selection of a rainfall time-intensity pattern. IDF curves are generally used to determine a design storm. Generally, although a real storm is variable over space as well as time, design storms do not normally have a strong representation of this effect. In some cases, a factor has been applied to the storm event to reduce its intensity as larger areas are considered. This is on the assumption that it is unlikely that an event will cover an entire large catchment at a uniform intensity, since the event will tend to cover only a part of the large catchment. Fringe areas may receive less rain than the point where the storm is centered.

The choice of a design event is a significant one, since the time (and space) distribution of precipitation has a marked impact on runoff rates. For instance, if runoff from pervious areas is significant, it may be necessary to try late peaking storms in addition to early peaking storm of the same total depth. Many approaches to synthetic rainfall event definition have been proposed. Representative examples are described below.

a) Uniform Rainfall

The most basic design storm, and one of only limited use, is the uniform rainfall event. This corresponds to a point on an IDF curve.

The duration of the event matches a duration on the IDF curve. The volume of the event is selected by taking the intensity on the IDF curve, and multiplying that value by the selected event duration.

(b) Chicago Storm

The Chicago storm in essence corresponds to all points on a single Intensity/Duration (ID) line on an IDF curve. The method generates a design event which has the property that each duration and intensity along the ID line is contained in some interval (duration) in the design storm. For any particular duration on the ID line, a particular intensity exists. There is an interval in the design storm, containing the peak intensity point, which contains the same particular intensity.

This storm has an effective and useful property in that all naturally occurring intensities and durations in the watershed records are, because of the way that the storm is derived (from the IDF curve), contained in the storm. This provides a reasonable basis for design.

Although it may be considered to be somewhat too intense in the very short interval immediately around the peak of the storm, because of the way it is derived, the method is still commonly used for small to medium urbanizing watersheds (0.1 to 10 sq. mi) where times to peak are short.

c) SCS Type II Storm

This storm was derived for use as a table of values that provide hyetograph values that have a reasonably representative distribution (e.g., Table 5.1). The event shape exists for long duration (up to 48 hour) and short duration (1 hour) events. The event shape, originally developed for larger watershed areas (10 sq. mi.) rural watersheds, but has been used in small urban watersheds as well. The longer duration SCS Type II storms have used for sizing detention facilities and at the same time providing a reasonable estimate of peak flow to provide sewer system sizing estimates.

TABLE 5.1 SCS Type II Rainfall Distribution for 3,6,12, and 24 Hour Durations

3 HOUR			6 HOUR			12 HOUR			24 HOUR		
Time	F_{inc} (%)	F_{cum} (%)	Time	F_{inc} (%)	F_{cum} (%)	Time	F_{inc} (%)	F_{cum} (%)	Time	F_{inc} (%)	F_{cum} (%)
						0.5	1	1			
			0.5	2	2	1.0	1	2	2	2	2
						1.5	1	3			
0.5	4	4	1.0	2	4	2.0	1	4	4	2	4
						2.5	2	6			
			1.5	4	8	3.0	2	8	6	4	8
						3.5	2	10			
1.0	8	12	2.0	4	12	4.0	2	12	8	4	12
						4.5	3	15			
			2.5	7	19	5.0	4	19	10	7	19
						5.5	6	25			
1.5	58	70	3.0	51	70	6.0	45	70	12	51	70
						6.5	9	79			
			3.5	13	83	7.0	4	83	14	13	83
						7.5	3	86			
2.0	19	89	4.0	6	89	8.0	3	89	16	6	89
						8.5	2	91			
			4.5	4	93	9.0	2	93	18	4	93
						9.5	2	95			
2.5	7	96	5.0	3	96	10.0	1	96	20	3	96
						10.5	1	97			
			5.5	2	98	11.0	1	98	11	2	98
						11.5	1	99			
3.0	4	100	6.0	2	100	12.0	1	100	24	2	100

where F_{inc} is the incremental infiltration,
F_{cum} is the cumulative infiltration, and
Time refers to the time at the end of the time interval.

5.3.3 Methods for Determining Runoff

The following sections provide a cursory review of common hydrologic concepts applied in Ontario. Complete discussions should be sought in the appropriate source references. To provide a uniform and understandable approach to the discussion of equations, minor deviations from commonly used symbols have been introduced.

The Basis for a Runoff Model

Analysis of hydrologic problems such as rainfall-runoff process is done, in the majority of cases, using mathematical models of one sort or another. In general, there are three categories of model. *Unit graph models* represent the catchment as a unit hydrograph, which is assumed to represent the pattern of catchment outflow over time, resulting from rainfall after all the losses are considered. This unit hydrograph is manipulated to achieve estimates for any given event. *Coefficient models* represent the catchment as an empirical relationship between various physical parameters and a peak flow or volume. The Rational Method which historically dominates drainage planning practice is an example of this. *Physically based models* attempt to actually simulate the major physical processes which determine the relationship between rainfall and runoff.

Loss Models

A number of modelling techniques are based on effective rainfall, in which a loss model is assumed which divides the rainfall intensity into losses and effective rainfall. Common methods for estimating losses follow.

a) Volumetric Coefficient

An effective means of estimating the cumulative runoff during the course of an event is provided by the following equation:

$$Q_v = C_v * (P - I_a) \qquad \textbf{(5.2)}$$

where:
- C_v = a volumetric runoff coefficient,
- Q_v = cumulative event runoff, greater than zero,
- P = cumulative event precipitation, and
- I_a = an initial abstraction.

Incremental event runoff volumes are generated by differencing cumulative event volumes. The method is probably most effective where impervious areas predominate.

b) Soil Conservation Service Method

A relationship developed by the U.S. Soil Conservation Service, has been used in many applications in Ontario. In this method, runoff volumes are generated based on a relationship which incorporates a parameter representing soil moisture storage (S), and an initial abstraction.

$$Q = \frac{(P - I_a)^2}{P + S - I_a} \qquad \textbf{(5.3)}$$

where: $\boldsymbol{S}$ = a loss parameter, and
$\boldsymbol{I_a}$ = initial abstraction = 0.2 $\boldsymbol{S}$.

Incremental event runoff volumes are generated by differencing cumulative event volumes.

The retention or potential storage in the soil is established by selecting a curve number (CN) which is a function of soil type, ground cover, and Antecedent Moisture Condition (AMC).

Tables 5-2 and 5.3 indicate the specific soil types, hydrologic classification, and corresponding curve numbers associated with the Soil Conservation Service (SCS) Curve Number (CN). The SCS CN method only gives an indication of the rainfall abstraction (or rainfall losses). Part of the rainfall abstraction is infiltration which is dependent on the soil moisture condition. Antecedent Moisture Condition (AMC) II is an assumed 'average' soil moisture condition. Rainfall abstraction also includes initial abstractions such as depression storage, infiltration prior to the start of runoff, and interception. Therefore, such an analysis can only provide an approximate indication of the infiltration volume.

TABLE 5.2 Runoff Curve Numbers

Runoff curve number (CN) for selected agricultural suburban and urban land use
(Antecedent Moisture Condition II and $I_a = 0.25$)

LAND USE DESCRIPTION	HYDROLOGIC SOIL GROUP			
	A	B	C	D
Cultivated land[1] :				
without conservation treatment	72	81	88	91
with conservation treatment	62	71	78	81
Pasture or range land :				
poor condition	68	79	86	89
good condition	39	61	74	80
Meadow : good condition	30	58	71	78
Wood or Forest land :				
thin stand, poor cover, no mulch	45	66	77	83
good cover[2]	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries etc				
good condition: grass cover on 75% or more of the area	39	61	74	80
fair condition : grass cover on 50% to 75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential:[3]				
Average lot size / Average % impervious				
1/8 acres or less / 65	77	85	90	92
1/4 acre / 38	61	75	83	87
1/3 acre / 30	57	72	81	86
1/2 acre / 25	54	70	80	85
1 acre / 20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers[5]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

[1] For a more detailed description of agricultural land use curve numbers refer to Nation Engineering Handbook, Section 4, Hydrology, Chapter 9, Aug. 1972.

[2] Good cover is protected from grazing and litter and brush cover soil.

[3] Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

[4] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[5] In some warmer climates of the country a curve number of 95 may be used.

TABLE 5-3. Hydrologic Properties of Soil Types for a 2 Hour, 25 mm Storm.

SOIL TYPE	SCS HYDROLOGIC CLASSIFICATION	CURVE NUMBER AMC II[1]	RAINFALL ABSTRACTION (mm)
Sand	A	38	23.1
Sandy Loam	AB	43	22.9
Loam	B	65	20.8
Silt Loam	BC	71	19.9
Clay Loam	C	76	18.8
Clay	D	81	17.4

[1] AMC II conditions represent an assumed 'average' soil moisture condition.

c) Horton Infiltration Equation

The infiltration capacity of the soil over time (***f***) can be represented as an exponential transition from an initial high rate ($\boldsymbol{f_o}$) to a lower rate ($\boldsymbol{f_c}$).

$$f = f_c + (f_o - f_c)\, e^{-\frac{t}{k}} \qquad \textbf{(5.4)}$$

Equation (5.4) is employed by integration to achieve an estimate of total loss, and excess rainfall is the difference between that loss and the applied rainfall. Typically, Horton's equation is applied in a model with a component that reduces runoff by an amount attributed to depression storage, similar to the above use of $\boldsymbol{I_a}$.

The effective rainfall hyetograph is used as input to a catchment model to produce a runoff hydrograph. This approach assumes that infiltration must stop at the end of the storm.

5.4 HYDROLOGIC ROUTING ANALYSIS

5.4.1 Surface Routing Models

Several specific approaches to surface routing have tended to dominate the practice of hydrology in Ontario.

Rational Method

An historically important method of estimating runoff rate is the Rational Method, which relates the peak runoff rate to precipitation intensity directly. The method is not as much used now as in the past, but is still relevant to hydrologic practice. The method is formulated as follows:

$$Q = k\,C\,i\,A \qquad \textbf{(5.5)}$$

where:

Q = peak runoff rate (L/s)
i = rainfall intensity (mm/hr)
A = land area (ha)
C = a runoff rate coefficient, and
k = a units conversion factor
= 10/3.6 (L/s per ha.mm/hr)

(Note that the rational method in imperial units gave rise to accepted coefficients which are different from the metric equivalents.)

The method can be related to the assumption that the maximum runoff rate associated with steady uniform rainfall occurs when all parts of the catchment contribute flow to the outlet.

It is important to recognise that the appropriate value of C depends on the magnitude of the storm and significantly higher values of C may be necessary for more extreme storm events (e.g. 25% increase in C for 100 year storm conditions).

The time of concentration (t_c) is comprised of two components:

- The time for overland flow to occur from a point on the perimeter of the catchment to a natural or artificial drainage conduit or channel (i.e., inlet time).

- The travel time in the conduit or channel to the outlet of the catchment (i.e., travel time).

The time of concentration is affected by a variety of physical factors, and is therefore not a constant. The time of concentration will vary according to:

- *Overland flow length*, with t_c generally proportional to length.
- *Average surface slope*, with t_c inversely proportional to surface slope.
- *Surface roughness*, with t_c is directly proportional to the roughness of the surface.
- *Depth of overland flow*, with t_c inversely proportional to flow depth.

Several methods are commonly used for estimating t_c:

- The SCS Kirpich formula, below, is used to provide a useful estimate of time of concentration as a function of maximum length of water travel, and the catchment slope.

$$t_c = 0.00013\ L^{0.77}\ S^{-0.385} \tag{5.6}$$

where:
L = maximum length of water travel, ft.
S = surface slope (***H/L***)
H = difference in elevation between the most remote point on the catchment and the outlet, ft.

- The Uplands method is used for estimating travel times for overland flow in watersheds with a variety of land covers. A total travel time is calculated by summing individual travel times for incremental flow lengths.

Unit Hydrograph Methods

A unit hydrograph is a distribution shape, used to represent the way that runoff leaves the catchment after one unit of rainfall excess volume is applied over a duration of one unit of time. The fundamental assumption of this method is that the runoff hydrograph follows a linear process. The unit hydrograph can be extended to other volumes and durations of excess rainfall:

- runoff from applied volumes different from one unit (over a unit of time) is estimated by multiplying ordinates of the unit hydrograph by the applied volume.
- runoff from applied volumes occurring over durations greater than one unit of time are

calculated by convoluting the response to a one unit volume applied over successive one unit intervals.

The ordinates of the unit hydrograph are expressed in units of discharge per unit depth of effective rainfall.

Kinematic Routing Schemes

It is possible to estimate catchment runoff by a simulation approach based on a representation of uniform flow on a plane.

$$Q = \frac{1}{n} * D_f^{5/3} * S_c^{1/2} \quad \textbf{(5.7)}$$

where: $\boldsymbol{Q}$ = flow rate per unit catchment width,
$\boldsymbol{S_c}$ = catchment surface slope,
$\boldsymbol{n}$ = Manning's roughness coefficient, and
$\boldsymbol{D_c}$ = Depth of flow on the catchment.

The relation can be solved over a time step by calculating runoff rate using the above equation, and by simultaneously solving for the change in flow depth as a net result of supply (precipitation) and loss (infiltration and outflow). It is possible to incorporate detention losses by reducing $\boldsymbol{D_c}$ by the an amount taken to be a depression storage.

5.4.2 Channel Routing

There is commonly a need in the practice of hydrology to estimate the effect of channels on hydrograph peaks and distributions. There may even be a need to determine how masses of flow are increased or decreased during their passage through the channel. The process of translating a flow from a watershed through a channel is known as a 'routing'. The translation of a flow hydrograph through a reservoir is also a routing. There are a variety of ways of accomplishing the routing. These include a number of very sophisticated hydraulic models or methods that address the solution of the St. Venant equations, or other fundamental relations describing open channel flow. These are used in instances where flood flows or surges are of particular importance. Generally, these more comprehensive methods can be referred to as hydraulic routing methods.

As well, there are a number of approximations and recognized routing techniques which more simply address the same problem. These methods, suitable in the context of the practice of hydrology where peak flows and flow routing effects are important, can be termed 'hydrologic routing methods'. Several of these are described below.

The Effects of Routing

One can describe the channel routing system as a storage volume, ***S***, which changes an input flow series, ***I***, into an output series, ***Q***. The storage volume is a function of depth in the channel, and of the channel shape. The input series is a function of time, and may be a hydrograph of any form. The output series, which is also a function of time, is evidently a result of the combined effect of the storage and of the input series.

The differences between the inflow hydrograph and the outflow hydrograph are either or both of i) a change in timing, or ii) a change in form. Unless a pump or other unusual condition is encountered, the net effect of routing is a reduction in peak, a delay in peak, and a spreading or flattening of the hydrograph.

Time Lag Routing

It is sometimes the case that the most significant effect of a channel is that the hydrograph is delayed, but not significantly attenuated. This can be the case where channels, particularly in the urban context, whose storage (i.e. channel volume) is limited. The lag can be estimated as a time interval ***T*** which is the time it takes water to travel the length of the channel. If this is the only feature of interest, the relation between ***Q*** and ***I*** is:

$$Q(t) = I(t-T) \quad \textbf{(4.8)}$$

Determination of the time lag involved may be by supposing a characteristic channel velocity over the length of the channel, or may be by using an estimation from a kinematic relationship such as the Manning Equation discussed above.

Even though the Time Lag method may be perfectly adequate, it is less often used in practice due to the simplicity and availability of other routing models.

The Muskingham Method

One of the most common methods of routing flows is the Muskingham Method. This method recognises the fact that channels often do have enough volume to attenuate a hydrograph. The method relates inflow to outflow by assessing the conservation of mass within the channel. Over a short time interval, one can write:

$$I_{avg}.\Delta t = Q_{avg}.\Delta t + \Delta S \quad \textbf{(5.9)}$$

or, taking the time at the beginning of the interval as '***n***' and at the end as '***n+1***', can write:

$$\frac{I_n+I_{n+1}}{2}=\frac{Q_n+Q_{n+1}}{2}+\frac{S_n+S_{n+1}}{\Delta t} \quad \textbf{(5.10)}$$

This can be rearranged and solved for the unknown of interest, flow ***Q*** at any particular time, by knowing i) the previous flow ***Q***, ii) the previous and present inflow, and iii) the previous amount of storage in the channel.

$$Q_{n+1}=I_n+I_{n+1}-Q_n-2.\frac{S_n+S_{n+1}}{\Delta t} \quad \textbf{(5.11)}$$

Since the storage ***S*** and flow ***Q*** are both unknown at the present time ***n+1***, solution of this equation requires an additional condition be imposed, namely that the relation between outflow ***Q*** and channel storage ***S*** be known. This relation might take a form which depends on the Mannings equation, may be a weir curve, or may be some other functions which allow calculation of outflow as a function of the depth or volume of flow in the channel. It may be that the relation

$$Q=f(S) \quad \textbf{(5.12)}$$

is of a form such that substitution for ***S*** and direct solution is possible, or it may be that the form of this relation is such that an iteration is required to solve the system.

The classic Muskingham form of this relation puts the equation in terms of three coeficients, as follows:

$$Q_{n+1}=C_0.I_{n+1}+C_1.I_n+C_2.Q_n \quad \textbf{(5.13)}$$

Each coefficient is a function of two parameters, ***K*** and ***x***, which can be solved graphically if an inflow and outflow hydrograph are known for a particular channel.

$$C_0=-\left(\frac{K.x-\frac{\Delta t}{2}}{K-K.x+\frac{\Delta t}{2}}\right) \quad \textbf{(5.14)}$$

$$C_1 = \left(\frac{K.x + \frac{\Delta t}{2}}{K - K.x + \frac{\Delta t}{2}}\right) \tag{5.15}$$

$$C_2 = \left(\frac{K - K.x - \frac{\Delta t}{2}}{K - K.x + \frac{\Delta t}{2}}\right) \tag{5.16}$$

To solve this system, it is recognised that cumulative storage is a linear function of the common term '***x.I* + *(1-x).Q***':

$$\int S.dt = f(x.I + (1-x).Q) \tag{5.17}$$

Trial values of ***x*** are selected, and when a straight line plot appears, the value of ***x*** has been determined, and the slope of that straight line has the value of ***K***. In fact, hand solution of the method is rarely done at present. However, the basic assumptions of continuity and of flow as a function of storage remain the foundation of most hydrologic routing methods.

Reservoir Routing

A major facet of stormwater management is in the need to control peak flows. This commonly is done by means of a reservoir, which may retain or detain the hydrograph and thereby reduce peaks. This need makes reservoir routing an important part of hydrologic analysis. Again, there are a number of models and approaches which have been offered, but the commonality of most approaches is that:

- the reservoir is taken as a volume which has a storage that is not dependent on surface slope (the surface is flat)

- the reservoir has an outlet which uniquely determines outflow as a function of elevation of water in the reservoir (a pipe or similar device)

These assumptions are reasonable in most urban hydrology applications, and allow a convienient approach to reservoir routing, which is strongly related to the channel routing described above.

As before, continuity is applied, and leads to a form which conveniently can be solved using techniques quite similar to the channel routing schemes introduced above.

Commonly, equation (5.10) is re-written in a form with all unknowns on one side, as follows:

$$\frac{2.S_{n+1}}{\Delta t} + Q_{n+1} = \frac{2.S_n}{\Delta t} - Q_n + I_n + I_{n+1} \tag{5.18}$$

The right hand side of (5.18) is all known, from conditions at the end of the previous time step. The value of the left hand side is therefore known for the new time step. Since the relation between ***S*** and ***Q*** is known, as a function of the outlet from the reservoir, it is possible to calculate the value of term on the left hand side as a function of reservoir storage or depth ***D***:

$$\frac{2.S_{n+1}}{\Delta t} + Q_{n+1} = f_1(S) = f_2(D) \tag{5.19}$$

In short, by plotting the relation $f_1(S)$ against ***S***, or $f_2(D)$ against ***D***, one can solve for storage and hence outflow from the reservoir at any time, if conditions at the end of the previous time step are known.

Variations of solution technique exist, but the basic principle in reservoir routing remains fairly common to the above sequence in most models. More complex reservoir models tend to concentrate more on operation or internal mixing issues as the next step in complexity, rather than on more sophisticated routing schemes.

5.5 SINGLE EVENT AND CONTINUOUS SIMULATION METHODS

The above algorithms for infiltration and routing processes can be packaged in single event models, or in continuous simulation models. The two are differentiated by:

- the computer code which allows the model to read long term precipitation records vs short term single event records, and

- the existence of algorithms which allow the model to simulate inter-event recovery.

The capacity of the soil to absorb moisture is not infinite, and neither is the capacity of depressions and other features that result in an initial abstraction. The continuous simulation model therefore has some means of having the appropriate parameters recover between events. Otherwise, the models types are not necessarily intrinsically different. The most pronounced differences in model function are related more to the needs of the user (i.e. short term, short time step information for design, compared to long term seasonally varied information for planning) than to hydrologic principles.

Mechanisms for this recovery can be physically based (using, for instance evaporation records to estimate the recovery of initial abstraction), empirical (using a recovery curve as a function of time only), or may lie somewhere in between (using a recovery algorithm which relates event recovery to a history of rainfall coupled to an empirical recovery rate). These are all potentially useful and reasonable, provided that they are correctly employed.

Continuous analysis involves the use of precipitation and other meteorological inputs to derive stormwater runoff for the entire year(s). Accordingly, most processes of the hydrologic cycle must be simulated such as snow accumulation and melt, evapotranspiration, infiltration, and runoff.

Continuous analysis is recommended for the estimation of BMP storage volumes. Continuous simulation has several advantages over precipitation design storms and design runoff events such as:

- Snow accumulation and melt is considered (spring runoff timing).
- The entire volume of runoff is routed through the design storage.
- Consideration is given to the runoff timing related to retention time.
- The relationship between precipitation and runoff is considered.
- Seasonal effects of runoff are considered (longer storms in the spring, more shorter storms in the summer).
- Continuous analysis results can be used to predict other essential watercourse characteristics (bedload movement and channel morphology responses).

For these and other reasons, continuous simulation is becoming a dominant part of hydrologic analysis.

The resulting runoff series should be analyzed on a seasonal basis to determine the appropriate BMP storage value. A seasonal analysis should be performed since there are seasonal effects for both water quality concerns and BMPs themselves.

On a watershed scale, or large master drainage area scale, continuous analysis could involve the use of relatively sophisticated models, and there is also the possibility of using simpler methods and equally effective methods for either regional or local water quality analyses. The results from a regional analysis could be easily extrapolated for use at a local level. In this sense, the local water quality BMP would still be designed based on some form of continuous analysis.

A variety of design event and continuous simulation models have been used in Ontario. Continuous simulation models which have been used include:

STORM: An early but very effective model targeted at Combined Sewage Control studies but generally useful in stormwater management. The model employs a variation of the SCS method and unit hydrograph techniques for hydrologic analysis.

SWMM: The dominant model in North American practice in urban hydrology, most commonly used in design event applications, but effective for continuous simulation as well. The model uses a kinematic routing scheme and several loss models, including Horton's equation, to represent surface hydrology.

HSPF: A major and complex model with comprehensive capabilities, requiring major data and other resources for use, but effective in undeveloped watersheds undergoing urbanization. A physically based model with a variety of soil and surface routing options available to represent hydrologic behavior.

QUALHYMO: A comprehensive model with applicability to BMP design and analysis of urbanization in developing watersheds. The model uses a variation of the SCS method and unit hydrograph techniques for hydrologic analysis.

GAWSER: A watershed model with effective algorithms for application to rural watersheds. Contains algorithms representative of physical processes, and originally developed for application in agricultural watersheds.

OTTSWMM: A variation on SWMM, with similar general capabilities, but focused on major/minor system analysis in urban watersheds.

Numerous others can be cited, and the field is still evolving. Selection of models should be done with care and in light of the particular application. The need for BMP analysis, extensive evaluation of river or lake impacts, design or planning assessments, or other factors will all have a strong impact on the 'best' model for the job. Ultimately, however, it is the ability of the modeler which is most important in deciding the outcome of a modelling exercise.