# A STUDY ON RAINFALL-RUNOFF CHARACTERISTICS OF URBAN CATCHMENT OF SUNGAI KERAYONG

by

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# LIST OF SYMBOLS

| | |
|---|---|
| $Q$ | Discharge |
| $A$ | Area |
| $C$ | Runoff coefficient |
| $I$ | Rainfall intensity |
| $i_n$ | Net rainfall intensity |
| $q_t$ | Discharge at time t |
| $q_0$ | Discharge at time=0 |
| $K$ | Fitting coefficient |
| $a$ | Constant |
| $b$ | Constant |
| $M$ | Constant |
| $t_c$ | Time of concentration |
| $t_o$ | Time of overland flow |
| $t_{ch}$ | Time of channel flow |
| $L$ | Length of catchment |
| $L_o$ | Length of overland plane |
| $L_{ch}$ | Length of flow path in channel |
| $S$ | Catchment slope |
| $S_o$ | Overland slope |
| $S_{ch}$ | Channel slope |
| $S_e$ | Equal area slope of the main stream/channel |
| $V_{avg}$ | Average velocity of flow |
| $F_c$ | Conversion factor (Bransby-Williams equation) |
| $A$ | Area (Manning equation) |
| $P$ | Wetted perimeter (Manning equation) |
| $R$ | Hydraulic radius |
| $y$ | Water level |
| $n$ | Manning roughness coefficient |
| $N_a$ | NAASRA retardance coefficient |
| $N_k$ | Kerby resistance coefficient |
| $N.S$ | Coefficient of determination (Nash and Sutcliffe, 1970) |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ARR | Australian Rainfall and Runoff |
| ARI | Average Recurrence Interval |
| CA | Cluster Analysis |
| DID | Department of Irrigation and Drainage |
| HTC | Humid Tropics Center |
| ILLUDAS | Illinois Urban Drainage Simulator |
| JUPEM | Department of Survey and Mapping, Malaysia |
| MSMA | Urban Stormwater Management Manual for Malaysia |
| NIWA | National Institute of Water and Atmospheric Research |
| PCA | Principal Component Analysis |
| SWMM | Stormwater Management Model |
| Tideda | Time Dependent Data |
| TRRL | British Transport and Road Research Laboratory |

# LIST OF PUBLICATIONS

1. **Baharudin, F.** and Abustan I. (2006). Determination of rainfall-runoff characteristics in urban areas: Sungai Kerayong catchment, Kuala Lumpur. Proceedings of National Seminar in Civil Engineering Research (SEPKA 2006), 19th-20th December, UTM.

2. **Baharudin, F.**, Abustan, I. and Sulaiman, A.H. (2007). A comparative study to estimate time of concentration for urban catchment: Sungai Kerayong, Kuala Lumpur. Persidangan Kebangsaan Awam 2007 (AWAM 07), 29th – 31st May, Langkawi.

# KAJIAN CIRI-CIRI HUJAN-AIR LARIAN DI KAWASAN TADAHAN BANDAR SUNGAI KERAYONG

## ABSTRAK

Tadahan Sungai Kerayong telah dipilih sebagai tadahan kajian bandar untuk mengkaji proses penjanaan air larian di bawah pengaruh iklim topika. Tiga objektif kajian telah ditentukan; pertama, untuk menghasilkan perhubungan antara hujan dan air larian menggunakan kaedah regresi linear; kedua, menentukan peratusan permukaan tidak telap dan dibandingkan dengan keputusan daripada perhubungan hujan-air larian, dan ketiga untuk menganggar masa tumpuan air. Kawasan tadahan dengan luas 48.3km$^2$ telah dibahagi kepada 3 sub kawasan. Peta gunatanah tadahan telah dihasilkan dari peta topografi digital dan imej satelit. Sejumlah 90 peristiwa banjir dari tahun 2000 hingga 2003 telah dipilih dan dianalisis untuk menentukan ciri-ciri hujan-air larian. Masa tumpuan air daripada kaedah hidrograf air larian terus dibandingkan dengan keputusan yang diperoleh melalui persamaan empirik. Keputusan regresi linear untuk hujan-air larian memberi anggaran permukaan tidak telap sebanyak 76.2% dan nilai storan lekukan 1.98mm. Keputusan ini hampir sama dengan anggaran daripada kaedah peta gunatanah iaitu 77.5%. Masa tumpuan air kawasan tadahan yang dikira dengan kaedah hidrograf air larian terus adalah 139.5 minit. Formula empirik NAASRA memberi keputusan terbaik dengan masa tumpuan air 141.8 minit dan nilai N.S -0.007.

# A STUDY ON RAINFALL-RUNOFF CHARACTERISTICS OF URBAN CATCHMENT OF SUNGAI KERAYONG

## ABSTRACT

Sungai Kerayong catchment was selected as an experimental urban catchment in order to study the runoff generation processes in tropical climate. The study sets three objectives, the first is to establish a reliable relationship between rainfall and runoff; the second is to estimate the percentage of impervious surface and compared the estimate with result from the rainfall-runoff correlation, and the third objective is to estimate the time of concentration of the catchment. The catchment which has an area of 48.3km$^2$ was divided into three subcatchments. The land use map was created using digital topographic maps and satellite images. A total of 90 single storm events from year 2000 to 2003 were selected and analyzed. The observed time of concentration values obtained from direct runoff hydrographs were compared with calculated values using four empirical equations. The linear regression technique gave estimate of impervious surface of 76.2% and depression storage of 1.98mm. This result is consistent with the estimate of impervious surface from the land use map which is 77.5%. The time of concentration obtained from direct runoff hydrographs was 139.5 minutes. Among the empirical formula, NAASRA formula is the most suitable with time of concentration of 141.8 minutes and N.S value of -0.007.

# CHAPTER 1
# INTRODUCTION

## 1.0 Introduction

Urban hydrology is a specific knowledge of hydrology applied in areas with very high concentration of human activities which deal with natural process. The continuous growth of population and massive development will affect the physical characteristics of an area and change the hydrological practice. A notable aspect of urbanization is the increase of impervious surfaces, which include paved streets, roads, parking lots and roofs. High impervious surfaces are the common cause for high runoff volumes as the soil infiltration capacity decreases (Figure 1.1). Thus, the drainage system for urban areas is relatively different from natural catchments whereby it is designated specifically to remove the runoff as fast as possible so that flooding can be prevented and the negative influence on transportation is minimized (Delleur, 2003).

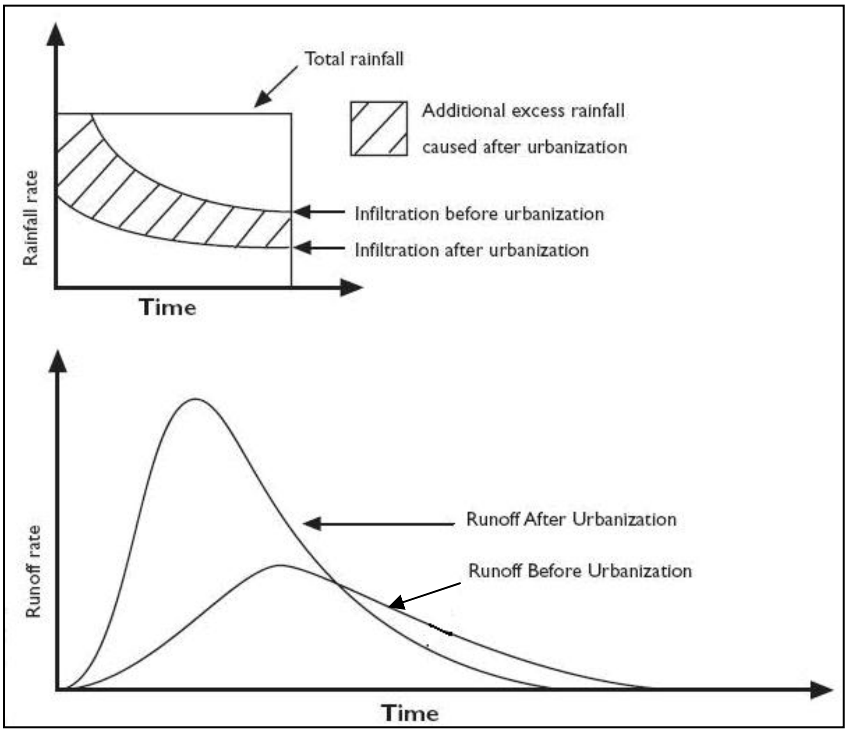
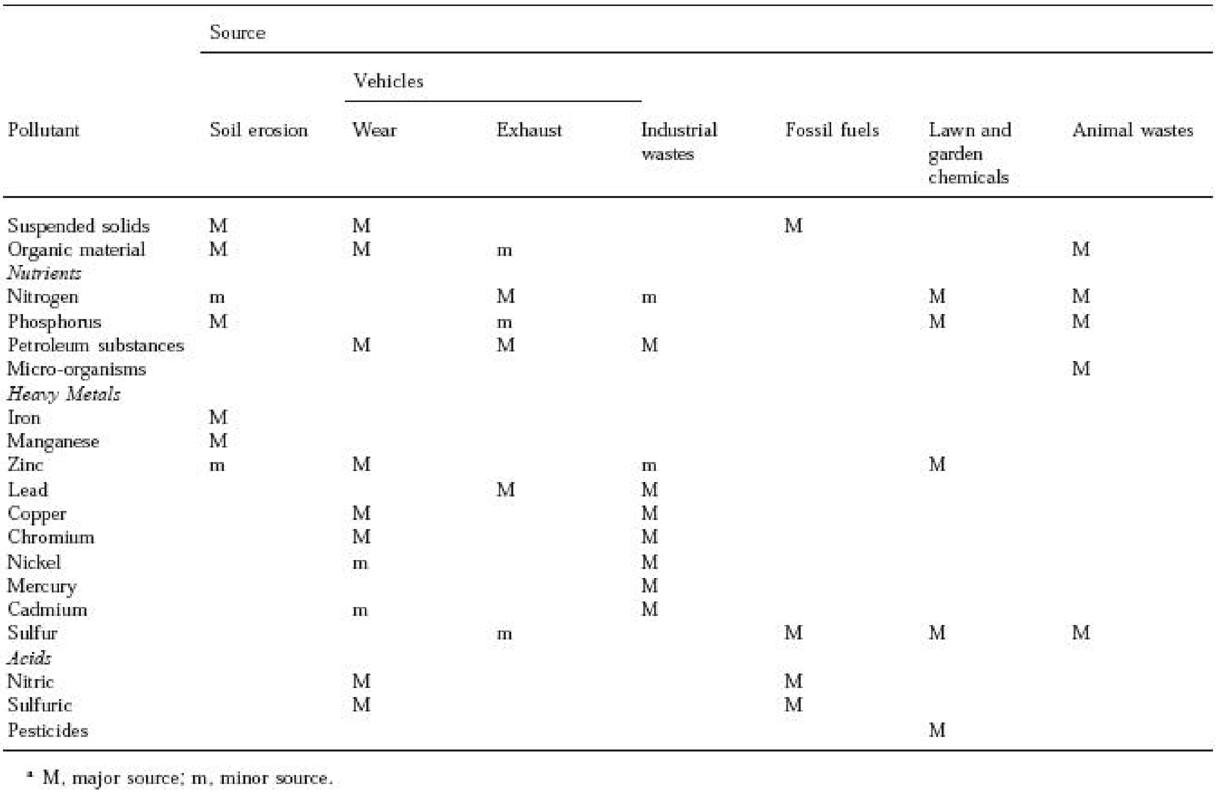


Figure 1.1: Urban hydrographs (www.uwsp.edu)

The common problem caused by urban runoff is the pollutants transported through the urban catchment area. Pollutants generated on and discharged from land surfaces as the result of the action of precipitation on and the subsequent movement of water over the land surface are commonly referred to as non-point pollutants or dispersed pollutants (Zoppou, 2001). Failures in urban infrastructures such as leachate from landfills and sewer infiltration also represent another source of pollutant. When these pollutants are transported into the receiving waters, it may cause both quality and quantity problems and this scenario can be detrimental to human health and to aquatic organisms. Table 1.1 shows examples of sources for non-point urban runoff pollutants.

Table 1.1: Sources of non-point urban runoff pollutants (Whipple, 1983)



| | Source | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Vehicles | | | | | |
| Pollutant | Soil erosion | Wear | Exhaust | Industrial wastes | Fossil fuels | Lawn and garden chemicals | Animal wastes |
| Suspended solids | M | M | | | M | | |
| Organic material | M | M | m | | | | M |
| *Nutrients* | | | | | | | |
| Nitrogen | m | | M | m | | M | M |
| Phosphorus | M | | m | | | M | M |
| Petroleum substances | | M | M | M | | | |
| Micro-organisms | | | | | | | M |
| *Heavy Metals* | | | | | | | |
| Iron | M | | | | | | |
| Manganese | M | | | | | | |
| Zinc | m | M | | m | | M | |
| Lead | | | M | M | | | |
| Copper | | M | | M | | | |
| Chromium | | M | | M | | | |
| Nickel | | m | | M | | | |
| Mercury | | | | M | | | |
| Cadmium | | m | | M | | | |
| Sulfur | | | m | | M | M | M |
| *Acids* | | | | | | | |
| Nitric | | M | | | M | | |
| Sulfuric | | M | | | M | | |
| Pesticides | | | | | | M | |

[a] M, major source; m, minor source.

Realizing the possible disastrous impacts that can occur, the approach of stormwater management and modeling has been improving throughout the years. It started in 1971 by the introduction of the stormwater management model (SWMM), a software which combines detailed modeling of hydrology, hydraulics, pollution transport and capable of performing continuous or single-event simulations. The knowledge began to expand whereby other models were developed aiming to tackle the same issue. Among them is the development of The Illinois Urban Drainage Simulator (ILLUDAS) in 1974, which was developed by the British Transport and Road Research Laboratory (TRRL), the Wallingford Storm Sewer Package (WASSP) developed in the U.K by the National Water Council (1981) and MOUSE developed by the Danish Hydraulic Institute (DHI) in 1996.

Malaysia particularly has also participated in the latest hydrologic research and studies in urban areas. As mentioned earlier, the vast development in the country has increased the percentage of impervious surfaces thus resulting in huge surface runoff volumes. In addition to the problem, inadequate drainage facilities also contributed to flash floods occurrence in urban areas (Anjum and Mohammad Kassim, 1999). Obviously, this worrying scenario has served as the problem statement for this study. Other researchers and scholars throughout the country have also taken the initiative to conduct studies particularly to ease the negative impacts from urban runoff and improve the hydrologic processes in urban areas (Sinnakaudan et. al., 2003; Abustan et. al., 2000; Desa and Niemczynowicz, 1996).

The support from the government is clearly seen through the Department of Irrigation and Drainage (DID) of Malaysia. On 21st June, 2000, the Cabinet had approved the "Urban Stormwater Management Manual for Malaysia" (MSMA) to replace *Planning and Design Procedures No. 1:Urban Drainage Design Standards and Procedures for Peninsular Malaysia – 1975,* which is effective from 1st January,

2001. The manual has 48 chapters and is divided into eleven parts which covers all the hydrology and hydraulics aspects for urban catchments. The primary goal of the manual is to provide guidance to all regulators, planners and designers who are involved in stormwater management and identifies a new direction for stormwater management in urban areas in Malaysia. By having a standard guideline, the construction of drainage system and detention facilities is becoming more consistent and ensures an optimum planning for land development of urban area.

Perhaps the best way in dealing with the urban hydrology issues is that all problems, whether flash floods or runoff quality or quantity, can no longer be evaluated in isolated cases but will have to be looked at in an integrated manner. It is hoped that by continuous research and extensive studies, the knowledge of urban hydrology can be understood better. It is not only to improve the knowledge itself, but also to provide a better environment for living for all mankind.

## 1.1 Problem Statement

The long standing issue on hydrology in this region is the study on runoff generation. Studies on runoff and its characteristics in tropical climate are still scarce. In Malaysian perspective, the urban stormwater designs applied was mainly based on foreign experience. The most notable case being if that the design chart of runoff coefficients in MSMA was adopted from the Australian data set (DID, 2000). The data may not be applicable to Malaysia and may lead to failures in designing structures for solving hydrologic problems such as flash floods. Proactive measures have to be taken to add more information on hydrological data in Malaysian urban areas.

## 1.2 Research Objectives

The research is designed to address the issue of rainfall and runoff processes in urban areas. The key objectives of this study are as follows:

1) To establish a reliable relationship between rainfall and runoff and obtain estimate for impervious surface and depression storage of the catchment.

2) To estimate the impervious surface by using satellite images and digital maps and compare the results with values obtained from the rainfall-runoff correlation.

3) To compare the time of concentration ($t_c$) of the studied catchment obtained by direct runoff hydrographs method and empirical equations.

## 1.3 Research Scope of Works

In order to achieve the objectives of the research, the following works are to be carried out:

1) Reviewing and searching literature on rainfall-runoff modeling and characteristics to establish a reliable rainfall-runoff relationship for Sungai Kerayong catchment.
2) Obtain the related rainfall and water level data from the Department of Irrigation (DID) Malaysia as well as the digital maps from the Department of Survey and Mapping.
3) Producing land use map and identifying the land characteristics to assess the impervious surface of the catchment area.

4) Assessing the direct runoff hydrographs of selected storm events for the time of concentration estimation, whereby four empirical equations are used to make comparison and verify the results.
5) From No. 4 above, estimate the time of concentration.
6) Compare the value in No. 5 above with the time of concentration derived from four empirical equations.

## 1.4 Structure of Thesis

### Chapter 1 - Introduction

This chapter introduces the definition and related issues on urban hydrology. Being the key topic of the research, it is important to describe a bit about the background of urban hydrology. The objectives and scope of works are also explained in this chapter.

### Chapter 2 – Literature Review

Chapter 2 describes the studies from previous researchers which are related to this research topic and being presented in sub-chapters for better understanding.

### Chapter 3 - Methodology

All related theories are presented and the methodology of the research is explained thoroughly in this chapter. A flow chart is presented to summarize the research activities. Data such as rainfall, water level, river survey and digital maps are collected and analyzed thoroughly.

### Chapter 4 - Results and Discussion

This chapter presents three main results. The first result is on the correlation of rainfall and runoff. The second is on the created land use map and the details on the land use characteristics. The final result involves the estimation of the time of concentration ($t_c$). The results are discussed within each section throughout this chapter.

### Chapter 5 - Conclusion

It is the final chapter for this thesis, which highlights the findings of this research and recommendations for further studies on the related topic.

# CHAPTER 2
# LITERATURE REVIEW

## 2.0 Introduction

Hydrology is a fascinating discipline of knowledge. It is concerned with water on, under and above the land surface; ocean waters are the domain of oceanography and the marine sciences. Scientific and engineering hydrology covers a broad field of interdisciplinary subjects that may be approached from various perspectives, including those of the geologists, chemists, civil engineers, environmental engineers, as well as hydrologists. In short, the definition of hydrology can be interpreted as presented by the U.S National Research Council in the following quote:

> *"Hydrology is the science that treats the waters of the Earth their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with the environment, including the relation to living things. The domain of hydrology embraces the full life history of water on Earth."*

## 2.1 The Hydrologic Cycle

Water does not remain locked up in the oceans, icecaps, groundwater system or the atmosphere. Instead, water is continually moving from one reservoir to another. This movement of water is called the hydrologic cycle. This phenomenon has even been noticed in the early days of mankind. Solomon, King of Israel, in writing Ecclesiastes 3000 years ago, provides a concise description of the hydrologic cycle:

> *" All rivers flow into the sea, yet the sea is never full. To the place the streams come from, there they return again."*

The main link in the water cycle in nature is exchange between the oceans and land, which includes not only quantitative renewal, but qualitative restoration as well. All types of natural waters are renewed annually, but the rates of renewal differ sharply. Water present in rivers is completely renewed every 16 days, but the renewal periods of glaciers, ground water, ocean water and lakes run to hundreds or thousand years (Shiklamanov, 1993). When slowly renewed resources are used by humans at a rapid rate, they effectively become non-renewable resources with subsequent disruptions of the natural cycle.

As for the general description for the hydrologic cycle, it is the continuous, unsteady circulation of the water resources from the atmosphere to and under the land surface and, by various processes, back to atmosphere (Walesh, 1989). It consists of various unsteady processes occurring either in the atmosphere or beneath the earth's surface and illustrated by Figure 2.1 below.

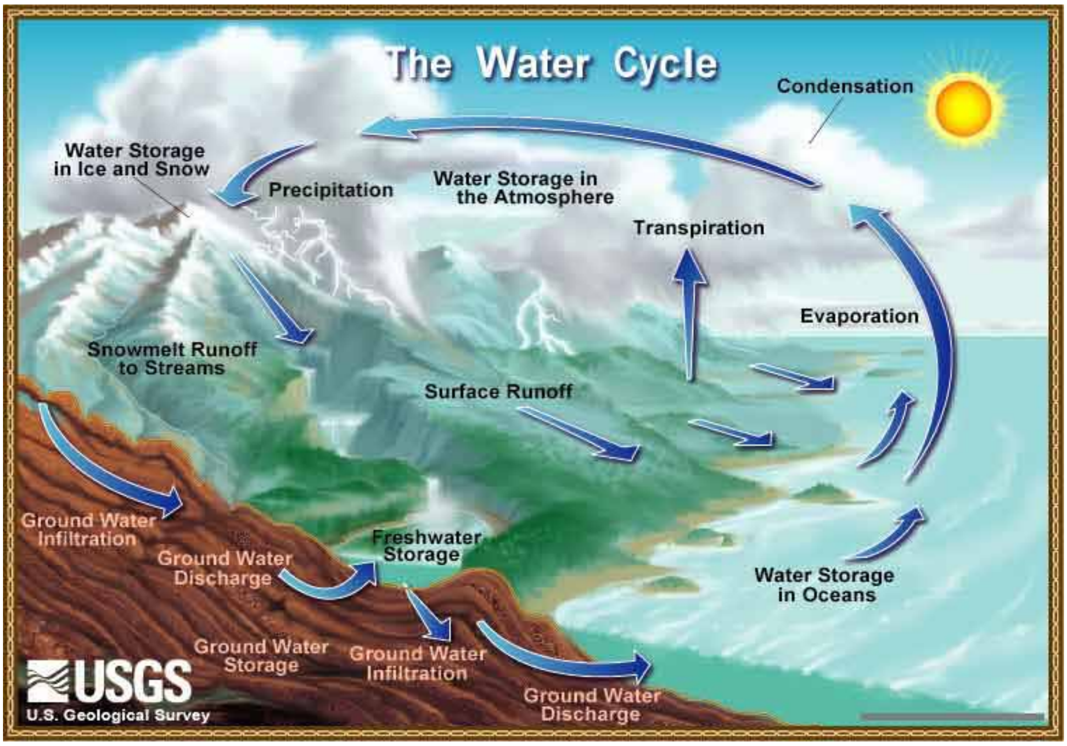


Figure 2.1: The hydrologic cycle (nd.water.usgs.gov)

Wurbs et. al. (2002) has explained the hydrological processes involved in the cycle. Energy from the sun results in evaporation of water from ocean and land surfaces and also causes differential heating and resultant movement of air masses. Water vapor is transported with the air masses and under the right conditions becomes precipitation. Evaporation from the oceans is the primary source of atmospheric vapor for precipitation, but evaporation from soil, streams, lakes and transpiration from vegetation also contribute. Precipitation runoff from the land becomes streamflow. Soil moisture replenishment, groundwater storage and subsurface flow occur as a result of water infiltrating into the ground while stream and groundwater flow convey water back to the oceans. Overall, the hydrologic processes by which water moves through the hydrologic cycle includes atmospheric movement of air masses, precipitation, evaporation, transpiration, infiltration, percolation, groundwater flow, surface runoff and streamflow.

An interesting truth to note about the whole process is, although water in the cycle is constantly in motion, it never leaves the earth. The earth itself is nearly a ‘closed system’ like a terrarium (Dasch, 2003). This shows that the earth neither gains nor loses much matter, including water. The same water existed on earth millions of years ago is most probably still is here today.

## 2.2 Urban Stormwater Management

Urban stormwater management is a knowledge used to understand, control, and utilize waters in their different forms within the hydrologic cycle. It is applied in developing areas with very high level of human interference with natural processes. The hydrological process in urban areas is similar to those in rural areas but they occur at smaller temporal and spatial scales in urban areas than in rural regions (Delleur, 2003). This brings essential differences with respect to theory, data collections and calculation methods. Undeveloped land in rural areas has very little surface runoff whereby most of the rainfall soaks into the top soil and evapotranspirates or migrate slowly through the soil mantle as interflow to the streams, lakes or estuaries.

Problems with management of urban stormwater are closely related to the concentration of population growth on a relatively small area. In order to enhance the living standard and better transportation system, large impervious areas are constructed. Most paved surfaces and rooftops allow no water to infiltrate, but instead divert water directly to storm channels and drains. The resulting effect on the hydrology of the receiving water is quite dramatic, especially for streams. A given rainstorm now produces significantly more runoff volume than before, and flow peaks are increased by a factor of 2 to more than 10 (Roesner et. al., 2001). The increased amount of water flowing to streams during storms causes larger floods, and floods build to a peak faster because of the rapid flow of water over smooth surfaces.

Large runoff volumes generated can accelerate transport pollutants and sediments from urban areas (Niemczynowicz, 1999). For example, the motor vehicles leave oils and exhaust residues on streets and household and industrial chemical products also can be collected on the pavement surfaces. These non-point source pollutants are readily washed off during storms, contaminating streams into which urban runoff flows. Careless disposal of hazardous wastes on streets or in storm drains also adds to the problems. Dasch (2003) has highlighted another impact of urbanization on runoff, which as a result of impervious area development, most precipitation has no chance to percolate downward to groundwater. Therefore, the supply of groundwater to wells is reduced.

Having known the impacts of urbanization to stormwater management, the traditional conveyance approach in stormwater management has been shifted during the 1970s to storage approach with a focus on detention, retention and recharge. Later on, during 1990s, stormwater came to be considered as a significant source of pollution and the main objectives of stormwater management shifted to protection of the natural water cycle and ecological systems by introduction of local source control, flow attenuation and treatment in natural or constructed biological systems such as ponds, wetlands, and root-zone treatment facilities (Niemczynowicz, 1999). Wurbs and Jones. (2002) has stressed the general purposes of stormwater management whereby they should enhance the quality of life in urban areas by reducing flood risk, minimizing the disruption of normal urban activities caused by storm runoff and the importance of protecting water quality in the urban areas.

Now it is time that the perspective of sustainability in relation to urban drainage should be taken more seriously. Sustainability points to the reintegration of water in the urban environment, working together with the hydrological cycle, observing ecological, environmental, landscape and recreation opportunities (Pompeo, 1999). For this reason, more research in stormwater management and development in structural and non-structural measures should be carried out comprehensively. The first step in an effective management strategy is to clearly define goals of the problem. This step is crucial in gaining public support, and it provides the basis for developing technological answers based on defensible scientific principles. Stormwater management programs that fail to clearly define objectives and develop approaches based on sound science are recipes for failure and litigation (Urbonas et. al., 2005).

## 2.3 Rainfall and Runoff

Rainfall is known as the main contributor to the generation of surface runoff. Therefore there is a significant and unique relationship between rainfall and surface runoff. By basic principle of hydrologic cycle, when rain falls, the first drops of water are intercepted by the leaves and stems of the vegetation. This is usually referred to as interception storage. Once they reach the ground surface, the water will infiltrate through the soil until it reaches a stage where the rate of rainfall intensity exceeds the infiltration capacity of the soil. The infiltration capacity of soil may vary depending on the soil texture and structure. For instant, soil composed of a high percentage of sand allows water to infiltrate through it quite rapidly because it has large, well connected pore spaces. Soils dominated by clay have low infiltration rates due to their smaller sized pore spaces. However, there is actually less total pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and commonly generate runoff sooner than clay soils (Ritter, 2006).

Apart from rainfall characteristics such as intensity, duration and distribution, there are other specific factors which have a direct bearing on the occurrence and volume of runoff. The most common factor is the soil type. Due to the variation of runoff production, different studies have been conducted according to particular soil conditions. For example, runoff production in blanket peat covered catchment would be rather different than urban area catchment. Blanket peat catchments exhibit flashy regimes, but little is known about the exact nature of runoff production processes within such catchments (Holden and Burt, 2003). In the past, many believed that blanket peatlands were able to attenuate floods and to sustain baseflow in streams and rivers during periods of low precipitation. However, recent studies have demonstrated that intact and degraded blanket peats are indeed extremely productive of runoff and have flashy regimes with little base flow contribution (Price, 1992; Burt et. al., 1990). The runoff generation in the area is also associated with the peat soil layering as the deeper layers may be an important overall contributor to runoff (Baird et. al., 1997).

Another factor that can affect the runoff production is vegetation. An area which is densely covered with vegetation produces less runoff than bare ground while the amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. Vegetation has a significant effect on the infiltration capacity of the soil. A dense vegetation cover shields the soil from the intense raindrop impact which eventually will cause a breakdown of the soil aggregate as well as soil dispersion with the consequence of driving fine soil particles into the upper soil pores. This results in clogging of the pores, formation of a thin but dense and compacted layer at the surface which highly reduces the infiltration capacity. This particular effect is often referred as to capping, crusting or sealing. In addition, the root system as well as organic matter in the soil increases the soil porosity thus allowing more water to infiltrate. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate and to evaporate. Kobatake et. al. (2000) assessed the impacts of vegetation recovery on runoff characteristics in the Ashio catchment, Japan. Large flood events from 1974 to 1998 were selected and the results show that the peak runoff coefficient has decreased from 0.59 to 0.38 throughout the years. The ratios of runoff volume of observed and calculated hydrographs also decreased from 1.25 to 0.91. Based on the fact that the catchment has been experiencing changes from polluted land due to mining and refining activities to steady recovery and growth of vegetation in the area, the findings have positively proven the theory of vegetation effects on runoff characteristics.

Slope and catchment size also influence the generation of surface runoff. Steep slopes in the headwaters of drainage basins tend to generate more runoff than the lowland areas. Overall mountain areas tend to receive more precipitation because they force air to be lifted and cooled. On gentle slopes, water may temporarily pond and later infiltrate, but in mountainsides, water tends to move downward more rapidly. Wemple and Jones (2003) examined the runoff production on forest roads in a steep, mountain catchment which support the earlier statement. Soils tend to be thinner on steep slopes, limiting storage of water, and where bedrock is exposed, little infiltration can occur. However, in some cases, accumulation of coarse sediment at the base of steep slopes soak up runoff from the cliffs above, turning into subsurface flow (Dasch, 2003). Size of catchment may have an effect to the runoff generation in terms of the runoff efficiency (volume of runoff per unit area). The larger the size of the catchment, the larger is the time of concentration and the smaller the runoff efficiency.

A study to assess the trends of rainfall-runoff characteristics in the Alzette river basin, Luxembourg was conducted by Pfister et. al. (2000). The relationship between atmospheric circulation pattern and streamflow has been emphasized as there has been a marked increase in the contribution of the westerly component of atmospheric circulation to rainfall since 1950. Principal component analysis (PCA) was used to compare the winter maximum daily flow with rainfall characteristics, including predominant atmospheric circulation patterns, rainfall intensity and average duration of rainfall events. By using the PCA method, the impact of zonal circulation, especially of the westerly airflow component, on maximum daily mean flow of the Alzette river has been identified with a strong correlation coefficient of 0.86. Time trends in the streamflow and rainfall characteristics were investigated by computing Kendall’s test. The results of Kendall’s tests showed positive trends in westerly airflow rainfall as well as in maximum daily flow are statistically significant and southwesterly airflow rainfall has also contributed to the increment of maximum daily mean flow depending on its interannual fluctuations.

Another study has been conducted by Merz et. al. (2006), regarding the surface generation process at the plot level in relation to rainfall events in a mountainous area of the Himalayas. The study makes use of event analysis with two different perspectives; the precipitation event analysis investigates runoff triggering mechanisms and erosion plot events are studied to investigate surface runoff generation. The results of the study indicated that rainfall events in the catchment can be divided into four major clusters with each cluster having different characteristics and the runoff events in the catchment are closely correlated to the event rainfall intensity parameters and the proposed clusters. The land use characteristics also contributed for the surface flow process whereby the infiltration excess flow is the main process in terms of runoff generation on degraded land while saturation excess overland flow is more relevant for agricultural land.

## 2.4 Rational Method

History has shown us the continuous evolution of drainage system design. Numerous methods and researches have been carried out in order to find suitable techniques in design applications. In the early 18th century the development of drains and canals designs were established by trial and error because there was insufficient information to derive methods to specify appropriate design flowrates. The introduction of Chezy channel friction formula in the 1770s and the collection of meteorological data in Europe in the early 19th century had helped the progress of the design procedures. In the 1840s, the Mulvaneys developed the rational method for flow estimation, inventing a recording rain gauge to measure intensity. From the design flow rates, a channel or pipe size could be established using hydraulic equations such as the Chezy or Manning formula (O'Loughlin et. al., 1996).

Rational method is well known as one of the basic approach to compute stormwater flows from rainfall by relating peak runoff to rainfall intensity through a proportionally factor. The first application of the rational method in urban drainage design was introduced by Kuichling (1889) in the U.S. and Lloyd Davies (1906) in the U.K. Since then, the method was gradually recognized and by 1940s, it became the standard method for street drainage system designs (O'Loughlin et. al., 1996). When the first flow rate or discharge formula was established, the rainfall intensities were not considered as a significant factor. Only by 1945, the rainfall intensities were recognized as an important proportion to be included in the following formula:

$$Q = \frac{C.I.A}{360} \tag{2.1}$$

where,

$Q$ = calculated flowrate ($m^3/s$),

$C$ = runoff coefficient,

$I$ = rainfall intensity (mm/h),

$A$ = area of catchment involved (ha).

Although the method can be considered as the most reliable approach in estimating the design storm peak runoff, experience has shown that it only provides satisfactory results on small catchments of up to 80 hectares only (DID, 2000). Some precautions should also be considered such as obtaining a good topographic map and defining the boundaries of the drainage area. A field inspection of the area should be carried out to examine the natural drainage divides. For larger catchments, storage and timing effects become significant and the hydrograph method is needed (DID, 2000). The Urban Stormwater Management Manual for Malaysia (MSMA) has outlined the assumptions used in the rational method. The assumptions are as follow:

1) The peak flow occurs when the entire catchment is contributing to the flow.
2) The rainfall intensity is uniform over time duration equal to the time of concentration, $t_c$.
3) The rainfall intensity is the same over the entire catchment area.
4) The Average Recurrence Interval (ARI) of the computed peak flow is the same as that of the rainfall intensity, ie; a 5 year ARI rainfall intensity will produce a 5 year ARI peak flow.

## 2.5 Hydrograph Separation

Hydrograph separation is a process of separating the major hydrograph components for analysis namely the surface runoff and the baseflow. Surface runoff (rainfall excess) is the water that enters the stream primarily by way of overland flow across the ground surface while baseflow is defined as water that enters the streams by way of deep sub-surface flow below the main water table and may include other components such as throughflow and interflow (ARR, 1987). Several methods have been proposed and used for separating the surface runoff and the baseflow but none of them have proven to be more superior as there is no ready basis for distinguishing both components in a stream at any instant (Linsley et. al., 1988). The selection of an appropriate method depends on the type and amount of measured data available, the desired accuracy for the design problem and the effort that the modeler wishes to expend.

Numerous academic explanations have been published in elaborating the separation methods. McCuen (1989) has outlined four types of baseflow separation, which are:

1) Constant-discharge baseflow separation
2) Constant-slope baseflow separation
3) Concave baseflow separation
4) Master depletion curve method

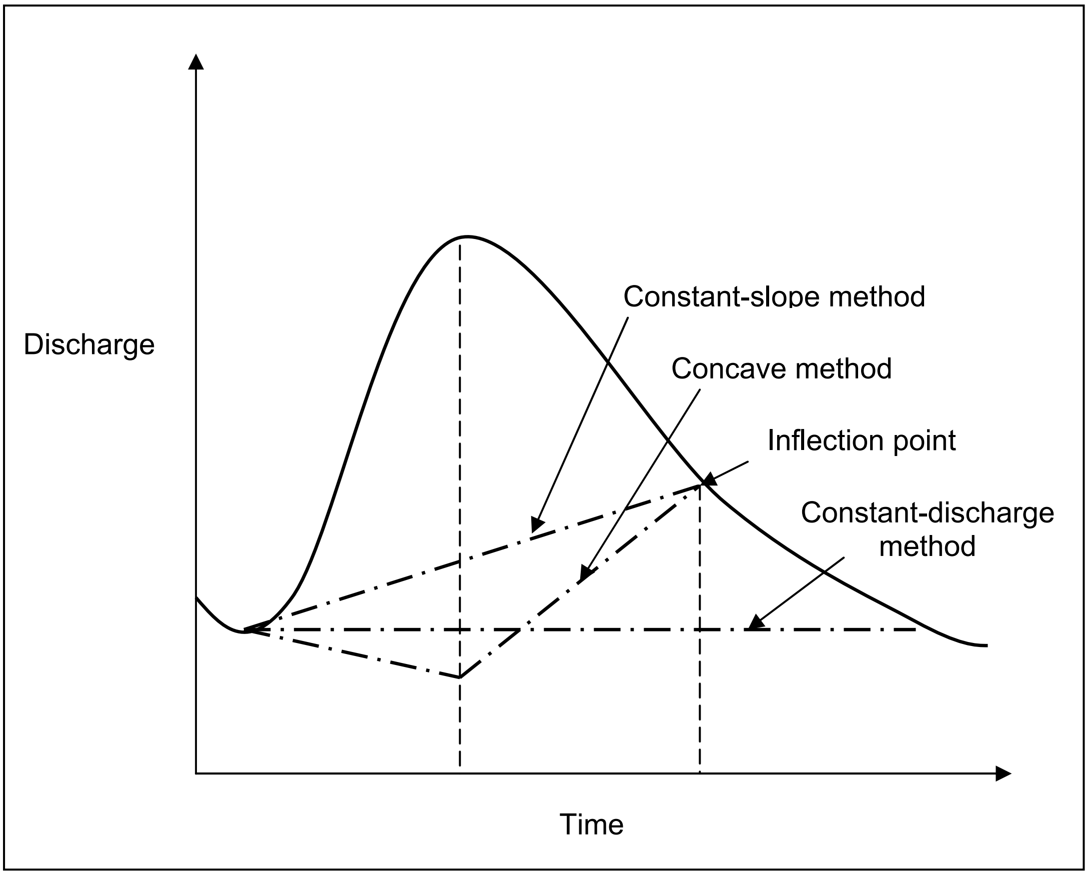


Figure 2.2: Baseflow separation methods (McCuen, 1989)

The easiest method to use is the constant discharge baseflow method. It is a straight line drawn from the lowest discharge rate at the start of the flood runoff and extends at a constant discharge rate until it intersects the recession limb of the hydrograph (Figure 2.2). The next method is the constant slope method whereby the inflection point of the hydrograph recession is being used. The estimation of the inflection point is indeed arbitrary but it can be defined by the point in which the hydrograph change from being concave to convex (i.e, the slope being greater than 1 to the slope being less than 1). Simply stated, it is the line drawn from the lowest discharge rate directly to the inflection point of the hydrograph.

The third method is called the concave baseflow separation. The baseflow is assumed to decrease until the time of the peak discharge of the storm hydrograph. From that point, the separation line is straight between that point and the inflection point on the recession as shown in Figure 2.2. Finally is the master depletion curve method which uses semi-logarithmic plots on the recession curves. A mathematical function form (Equation 2.2) which fits the data is applied to construct the curve.

$$q_t = q_o e^{-Kt} \tag{2.2}$$

where,

$q_t$ = discharge at time t,

$q_o$ = discharge at time t = 0,

$K$ = fitting coefficient.

The Australian Rainfall and Runoff (1987) has proposed another method in which the separation of baseflow is achieved by drawing tangents to the average recession curves at the points of start and finish of the hydrograph and drawing a straight line between these tangents points. However there is another way of connecting the two tangents points. The discharge rate from point A on Figure 2.3 is extended with a straight line until it reaches to point below the peak of the hydrograph and then connected to the point B by a smooth curve as shown in Figure 2.3.

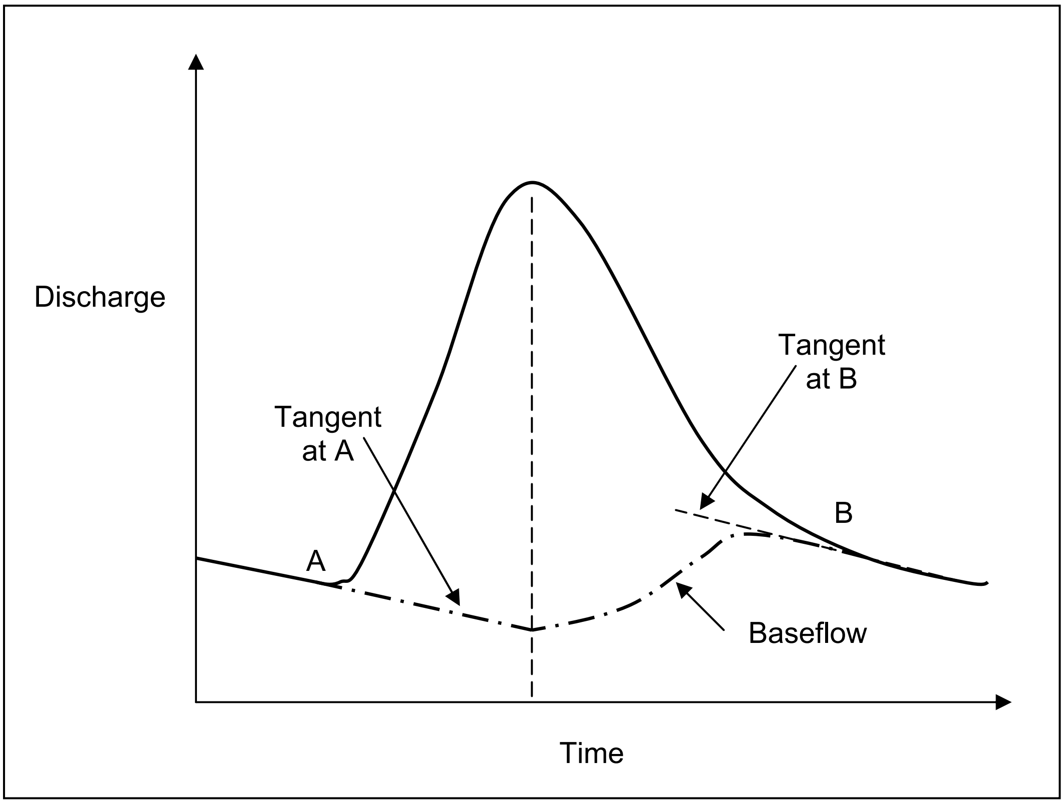


Figure 2.3: Australian Rainfall and Runoff baseflow separation (ARR, 1987)

Scholars around the world are continuously researching new techniques and methods for the hydrograph separation. As an example, a study conducted by Szilagyi and Parlange (1998) proposed a baseflow separation technique applicable for individual flood events, with analytical solutions of the Boussinesq equation. Demonstrated in four catchments in United States with total of 32 flood events, the technique is based on the governing equation for flow in saturated porous media and implying assumptions that a horizontal impermeable layer underlies a Dupuit aquifer which is drained by a fully penetrating stream. The hydrograph is characterized into three major regions and the analysis involved some essential equations as shown in Equations 2.3 and 2.4.

$$\frac{dQ(t)}{dt} = -aQ^{b}(t) \qquad (2.3)$$

$$Q(t) = \left(Q_0^{\,1-b} - (1-b)at\right)^{\frac{1}{1-b}} \text{, if b} \neq 1;$$

$$Q(t) = Q_0 e^{-at} \text{, if b = 1} \qquad (2.4)$$

where,

$Q$ = measured discharge,

$a$ and $b$ = constants.

To summarize the proposed baseflow separation technique, the following steps have been highlighted by the authors as well as the simplified diagram in Figure 2.4.

1) Plot log (-ΔQ / Δt) versus log (Q) for the receding limb of the flood hydrograph with an appropriate value for Δt.
2) Identification of region A at low discharge values characterized with a slope of 1.5.
3) Identification of region B to the right of region A with a slope steeper than 1.5. Draw a straight line with a slope of 1.5 through the smallest discharge value (i.e. $Q_{AB}$) in region B and extend it up to region C (i.e. to $Q_{BC}$, the maximum discharge value in the steepest slope region). Region C contains the highest rates of change in runoff values.
4) Transform the straight line in region B into Q(t) values by the application of Equations 2.2 and 2.3. The baseflow maximum results at the backward propagated time equaling the elapsed time between the observed $Q_{AB}$ and $Q_{BC}$ discharge values.
5) Draw a straight line between the beginning of the rising hydrograph and the estimated baseflow maximum. This part, by default, is arbitrary.

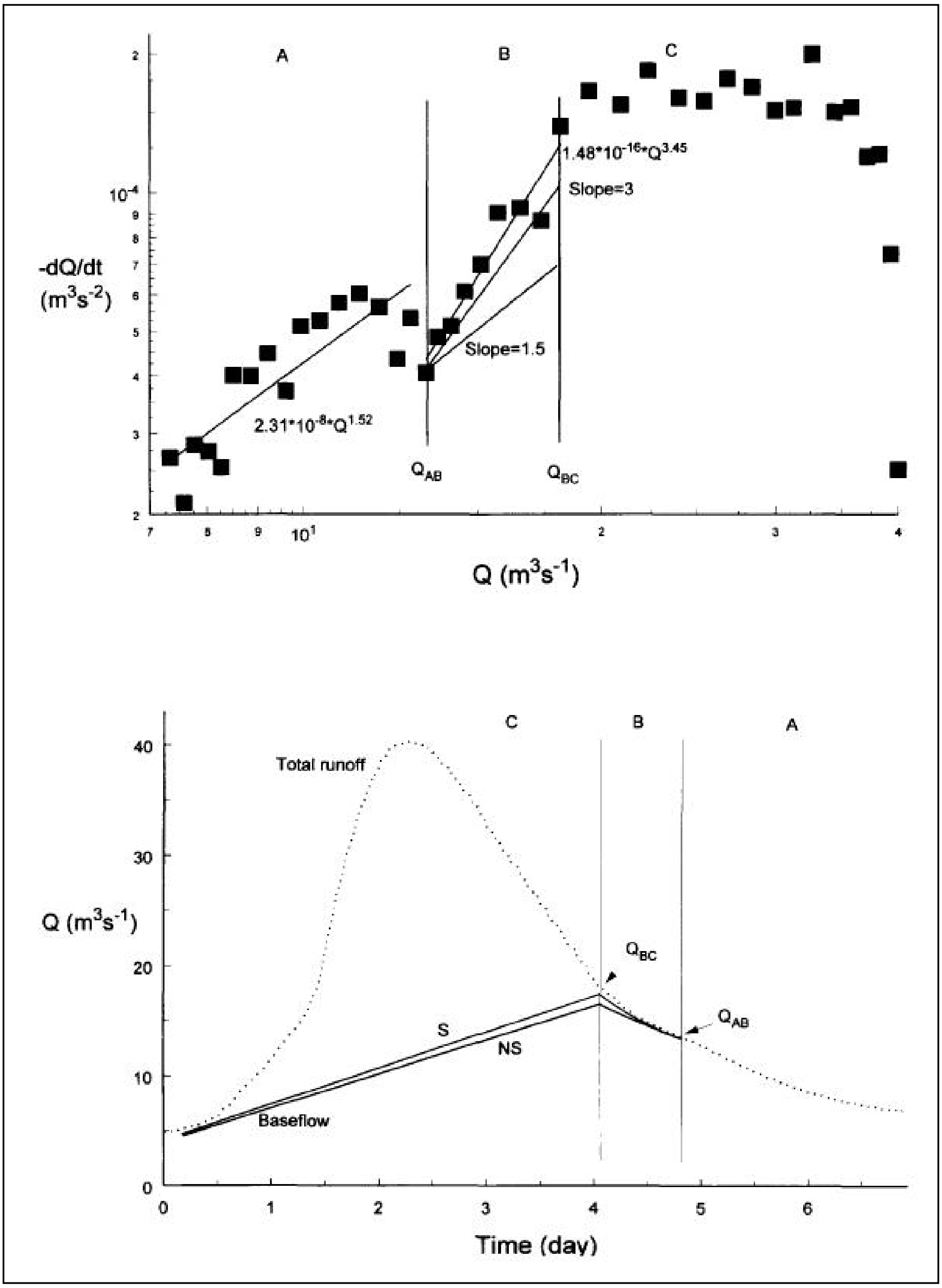


Figure 2.4: Diagram of Baseflow Separation by Analytical Solutions of the Boussinesq Equation (Szilagyi and Parlange, 1998)

Shukla et. al. (2000) proposed another advance baseflow separation procedure using water quantity and quality data at two experimental catchments, the Nomini Creek (NC) and Owl Run (OR) located in Virginia. Flow rate was used to represent the water quantity while the water quality entity included nitrate ($NO_3$), total Kjeldahl nitrogen (TKN) and total suspended solids (TSS). A multivariate statistical procedure, which is the cluster analysis (CA) was utilized to group the water quality samples on the storm hydrograph to identify the end point of the baseflow separation line. The CA method was compared with two commonly used methods which are the straight line method and constant slope method to validate the results. Overall, the baseflow volume estimations from the CA method were found to be greater than the results obtained by the straight line method and the constant slope method. For the NC watershed, there was significant evidence ($p < 0.047$) that the baseflow estimates were in the order CA is greater than constant slope method, and the constant slope method is equals to straight line method, while the statistically significant order for the OR watershed was CA equals to constant slope method, and the constant slope method is greater than the straight line method.