Review of Methods in Estimating Surface Runoff from Natural Terrain

GEO Report No. 292

Fugro Scott Wilson Joint Venture

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

Review of Methods in Estimating Surface Runoff from Natural Terrain

GEO Report No. 292

Fugro Scott Wilson Joint Venture

This report was originally produced by Fugro Scott Wilson Joint Venture in October 2013 under Consultancy Agreement No. CE 10/2009 (GE) for the sole and specific use of the Government of the Hong Kong Special Administrative Region

Table of Contents
Table of Contents
Table of Contents

First published, November 2013

Prepared by:

Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

Table of Contents
Table of Contents
Table of Contents

Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

The Geotechnical Engineering Office also produces documents specifically for publication in print. These include guidance documents and results of comprehensive reviews. They can also be downloaded from the above website.

These publications and the printed GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the second last page of this report.

H.N. Wong
Head, Geotechnical Engineering Office
November 2013

Table of Contents
Table of Contents
Table of Contents

Foreword

Slope surface drainage plays an important role in preventing erosion and improving slope stability. Inadequate slope surface drainage could lead to serious landslides and/or flooding. Guidelines on estimating surface runoff for design of slope drainage works in Hong Kong are given in various manuals and guidance notes issued by the Geotechnical Engineering Office of Civil Engineering and Development Department (GEO/CEDD), Highways Department and Drainage Services Department.

This Report reviews the prevailing practices in surface runoff estimation in Hong Kong and various overseas countries. It includes an assessment of the stream gauge data collected by the Water Supplies Department for four local watersheds to enhance the understanding of the surface runoff characteristics in natural terrain. Various methods of estimating surface runoff have been reviewed and the continued use of the Rational Method with the Bransby-Williams equation is recommended. However, it was found that the peak runoffs estimated by the Rational Method were exceeded by recorded flows in the watersheds in some rainstorms with return periods of 17 years or less, which were much less than the design return period of 200 years. Based on this finding and the review, this Report discusses and recommends the use of weighted average runoff coefficient for natural terrain catchments to take account of different ground conditions within the watersheds, and an increase in the runoff coefficient of steep natural terrain by at least 50% to allow for the effect of antecedent rainfall.

This Report was prepared as part of the Landslide Investigation Consultancy for landslides occurring in Kowloon and the New Territories in 2010 and 2011, for GEO/CEDD, under Agreement No. CE 10/2009 (GE).

This Report was prepared by Mr K.K. Pang of Fugro (Hong Kong) Limited, with the support of Dr C.M. Bill Mok of AMEC Environment and Infrastructure (Adjunct Professor at the University of Waterloo and Affiliated Professor at the Technical University of Munich), Mr J.M. Shen of Fugro (Hong Kong) Limited, Messrs K.K.S. Ho, J.S.H. Kwan, M.H.C. Chan, W.L. Shum and H.W.K. Lam of GEO/CEDD. Professor J.H.W. Lee of the Hong Kong University of Science and Technology provided insightful comments on the study. Dr C.M. Bill Mok independently reviewed the findings of the study. All their contributions are gratefully acknowledged.

Y.C. Koo
Project Director
Fugro Scott Wilson Joint Venture
Agreement No. CE 10/2009 (GE)
Study of Landslides Occurring in Kowloon and the New Territories

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

List of Tables

Table of Contents
Table of Contents
Table of Contents

List of Figures

Table of Contents
Table of Contents
Table of Contents

1 Introduction

Slope surface drainage plays an important role in preventing erosion and improving slope stability in Hong Kong. Inadequate slope surface drainage could lead to serious landslides and/or flooding. Design guidelines for drainage works in Hong Kong are given in various manuals and guidance notes issued by different departments including the Drainage Services Department (DSD), Highways Department (HyD) and Geotechnical Engineering Office (GEO) of Civil Engineering and Development Department (CEDD). Different guidance documents have been established for application in different areas. For example, GEO (1984) recommends guidelines pertaining to drainage design for man-made slopes, and DSD (2013) aims at giving guidance and standards for planning and management of stormwater drainage systems.

A review of the design and detailing of surface drainage provisions has been made by Tang & Cheung (2007), who recommended some improvements to the drainage detailing and suggested areas that warrant further study. As a follow-up to Tang & Cheung (op cit), this study examines the prevailing practice adopted by local practitioners in surface drainage design for natural terrain hazard mitigation works, and reviews the consistency of the prevailing practice in the local industry. This study also investigates the practicability and usefulness of estimating surface runoff from natural terrain by methods other than the Rational Method. Reviews of the applicability, basis and estimation methodology of key parameters used in the Rational Method, including runoff coefficient and time of concentration, are presented in this report.

This Study has also analysed the stream gauge data collected by the Water Supplies Department (WSD) for four local watersheds with a view to enhancing the understanding of the surface runoff characteristics of natural terrain in Hong Kong.

2 Design Guidelines on Drainage Works

2.1 Local Design Guidelines

Local guidelines for the design of surface drainage provisions in Hong Kong are given in various publications. The most commonly used documents are the Stormwater Drainage Manual (DSD, 2013) and the Geotechnical Manual for Slopes (GEO, 1984). The following paragraphs summarise the relevant recommendations given in these two publications on the estimation of surface runoff. A brief account of other publications on surface runoff estimation in Hong Kong is given in Appendix A. A summary of the commonly used analytical methods for estimating surface runoff is given in Appendix B.

The Stormwater Drainage Manual providing guidance on planning and management of stormwater drainage facilities was first published by DSD in 1994. The Stormwater Drainage Manual was later updated in 2000 (DSD, 2000) and recently further updated in 2013 (DSD, 2013). DSD (2013) describes the Rational Method, time-area method, unit hydrograph method and reservoir routing method as the deterministic approaches to estimate surface runoff for the design of stormwater drainage. According to DSD (2013), the Rational Method should not be used for areas larger than 1.5 km^2 without subdividing the

Table of Contents
Table of Contents
Table of Contents
Table of Contents

overall catchment into smaller catchments, and the effect of flood routing due to the presence of drainage channels should be considered.

The Rational Method considers uniform rainfall over time and area. The peak runoff is computed by:

$$Q = CiA / 3600 \quad \text{.....} \quad (2.1)$$

where Q = peak surface runoff (in litres/s)
i = design rainfall intensity (in mm/hr)
A = area of catchment (in m^2)
C = runoff coefficient (dimensionless)

The surface runoff is the water flow on the surface of a catchment which comprises direct runoff and baseflow (see Figure 2.1). Direct runoff is the immediate discharge in the catchment in response to a rainfall event. Baseflow is the delayed discharge in the catchment derived from the underground water stored in the ground which could be a result of antecedent rainfall.

Time of concentration (t_c) is the time needed for water to flow overland from the most remote point in a catchment to its outlet. Peak surface runoff occurs when the duration of the design rainfall with a constant intensity is equal to the time of concentration of the catchment.

Runoff coefficient (C) is the ratio of surface runoff to rainfall depending on the land use and the gradient of the ground. The coefficient involves empirical factors that cannot be determined precisely. DSD (2013) recommends the use of runoff coefficients of 0.05 to 0.35 for undeveloped grassland, 0.4 to 0.9 for steep natural slopes or areas where a shallow soil surface is underlain by an impervious rock layer, and 1.0 for developed urban areas. It is noted that the recommended values of runoff coefficient for undeveloped grassland (i.e. 0.05 to 0.35) coincide with the values recommended by WPCF (1963), which remarked that the coefficient was established based on rainstorms of return periods of 5 years to 10 years and the use of higher values of the coefficient could be required as appropriate.

DSD (2013) indicates that the Bransby-Williams equation is commonly used in Hong Kong to estimate the time of concentration of a natural catchment. The Bransby-Williams equation is given as follows:

$$t_c = \frac{0.14465L}{H^{0.2}A^{0.1}} \quad \text{.....} \quad (2.2)$$

where t_c = time of concentration (in min)
A = catchment area (in m^2)
H = average slope (in m per 100 m), measured along the line of natural flow, from the summit of the catchment to the point under consideration
L = distance (on plan) measured along the line of natural flow between the summit and the point under consideration (in m)

Table of Contents
Table of Contents
Table of Contents
Table of Contents

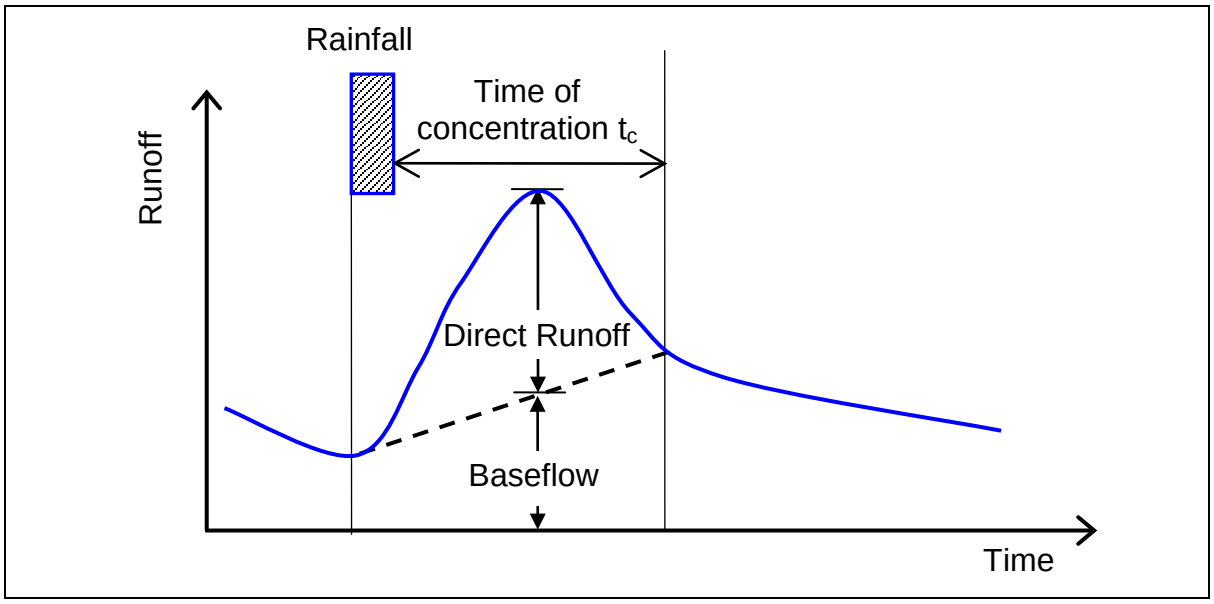


Figure 2.1 Surface Runoff and Time of Concentration

GEO (1984) provides guidance for the design, construction and maintenance of slopes and site formation works in Hong Kong. GEO (1984) recommends the use of the Rational Method for the determination of runoff from relatively small catchments in Hong Kong because the method is simple and straightforward.

For natural terrain catchments, GEO (1984) recommends the use of the Bransby-Williams equation to estimate the time of concentration. Where the stream course has been channelled and straightened, the time of concentration could be much shorter than that calculated using the Bransby-Williams equation. For such cases, GEO (1984) recommends that the time of concentration should be calculated by adding the time of travel within the drainage channel to the time of concentration as calculated using the Bransby-Williams equation for the most remote sub-catchment to the drainage channel.

GEO (1984) recommends adopting a 200-year return period storm and a runoff coefficient of 1.0 for the design of drainage works on man-made slopes.

2.2 International Design Guidelines

An overview of the guidelines on the design of stormwater drainage in various places, including the United States (USA), United Kingdom (UK), Canada, Australia, France, Mainland China and Taiwan is given in Appendix C. A summary of these design guidelines is given in Table 2.1, in which the design guidelines in Hong Kong are also presented for comparison.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 2.1 Summary of Design Guidelines Adopted in Various Places (Sheet 1 of 2)

Place	*Methods Commonly Used in Estimating Surface Runoff	*Maximum Drainage Area Allowed for Rational Method	*Methods Commonly Used in Estimating Time of Concentration	Range of Runoff Coefficients (*C*) Recommended for Rational Method	Design Return Period
Hong Kong	Rational Method	1.5 km^2	Bransby-Williams equation	DSD (2013): Surface Characteristic — *C* Asphalt — 0.7 - 0.95 Concrete — 0.8 - 0.95 Brick — 0.7 - 0.85 Grassland Flat (silty/clayey soil) — 0.13 - 0.25 Steep (silty/clayey soil) — 0.25 - 0.35 Flat (sandy soil) — 0.05 - 0.15 Steep (sandy soil) — 0.15 - 0.20 Steep natural slopes or shallow soil underlain by impervious rock layer, *C* may be taken as 0.4-0.9. GEO (1984): 1.0 for man-made slopes.	DSD (2013): 50 years for rural drainage and 200 years for urban drainage. GEO (1984): 200 years for slope drains.
USA	Rational Method, CN Method, Hydrograph Method	0.8 km^2	Papadakis & Kazan's equation, Kirpich equation, hydraulic flow equations	Steep lawn area (heavy soil): 0.25-0.35 Urban area: 0.5-0.95 *Higher values are usually appropriate for steeply sloped areas and longer return periods because infiltration and other losses have a proportionally smaller effect on runoff in these cases.	2 years to 100 years (depending on the land uses and States, e.g. 2 years for roadside ditch in Florida and 100 years for culvert in watershed in Connecticut)

Table of Contents Table of Contents Table of Contents Table of Contents

Table 2.1 Summary of Design Guidelines Adopted in Various Places (Sheet 2 of 2)

Place	*Methods Commonly Used in Estimating Surface Runoff	*Maximum Drainage Area Allowed for Rational Method	*Methods Commonly Used in Estimating Time of Concentration	Range of Runoff Coefficients (*C*) Recommended for Rational Method	Design Return Period
UK	Rational Method, Statistical Methods (WP models)	1.5 km^2	Bransby-Williams equation	Varying from 0.05 for flat sandy areas to 0.95 for urban surfaces.	10 years to 100 years
Australia	Rational Method, Unit Hydrograph Method	5 km^2	Kinematic wave formula	Vegetation covered surface: low permeability: 0.38-0.84 medium permeability: 0.29-0.84 high permeability: 0.01-0.64 Urban Area: 0.87-1 (for 100 years recurrence interval)	1 year to 100 years
France	Rational Method, Hydrograph Method	-	Hydraulic flow equations	Urban area: 0.2-0.9	10 years to 50 years
Taiwan	Rational Method	10 km^2	Rziha equation, Kraven formula, California formula	Hill slope: 0.7-0.8 Forest: 0.5-0.75 Agricultural area : 0.45-0.6 Urban area: 0.85-1	5 years to 50 years
China	Rational Method	-	-	Unpaved area: 0.25-0.35 Gravels or asphalt: 0.55-0.65 Paved area: 0.85-0.95	20 years to 200 years
Canada	Rational Method, Hydrograph Method, CN method	10 km^2	Bransby-Williams equation, hydraulic flow equations	Clayey soil: 0.4-0.55 Well drained soil: 0.4-0.2 Paved urban : 0.2-0.95	5 years to 200 years

* Note: Refer to Appendix C for more details.

2.2.1 Surface Runoff Estimation Models

As can be seen in Table 2.1, the Rational Method is by far the most commonly used method worldwide for estimating surface runoff of small catchment areas of less than 0.8 km^2 to 10 km^2.

Other methods, such as the Curve Number (CN) method, hydrograph method and statistical runoff models, are widely used in North America. However, these methods which require the establishment of various empirical relationships between meteorological and surface hydrological parameters are not commonly adopted in other places. These empirical relationships are location specific, and have not been established for the conditions in Hong Kong. On the other hand, the Rational Method has been adopted prevailingly in local practice for many years and appears to yield reasonable estimates of the surface runoff (see Section 5).

2.3 Time of Concentration

As can be seen in Table 2.1, the time of concentration is estimated by empirical equations such as the Papadakis and Kazan's equation, Kirpich equation and Bransby-Williams equation. The latter one is recommended by DSD (2013) and GEO (1984) for estimating the time of concentration in Hong Kong. Hydraulic flow equations are commonly used in the USA and elsewhere. Further discussions of these methods are given in Section 5 and Appendix B.

2.4 Runoff Coefficient

Table 2.1 shows that even under similar land use conditions, different places adopt different runoff coefficients. In general, the runoff coefficient recommended for urban areas or paved land ranges from 0.8 to 1.0, yet it could be as low as 0.2 as adopted in France and Canada. For vegetated land and natural terrain, the recommended runoff coefficients are generally lower than those recommended for urban areas or paved land. Australia adopts a runoff coefficient as low as 0.01 for vegetated land with high permeability.

In Hong Kong, GEO (1984) recommends a runoff coefficient of 1.0 for the drainage design of man-made slopes with a view to providing robust design that makes allowance for silting of channels. DSD (2013) recommends a runoff coefficient of 0.4 to 0.9 for steep natural slopes or areas where a shallow soil surface is underlain by an impervious rock layer. It is worth noting that DSD (2013) considers the value of runoff coefficient also depends on, inter alia, the antecedent moisture condition of the ground. A review of some of the geotechnical design reports recently completed by local practitioners indicates that a range of runoff coefficients of 0.4 to 1.0 has been adopted for the design of surface drains on natural terrain under the Landslip Prevention and Mitigation (LPMit) Programme. Further discussion of this subject is given in Section 3.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

2.5 Design Return Period

Most overseas countries adopt a return period of less than 100 years for drainage design (Table 2.1). In Hong Kong, DSD (2013) recommends a design return period of 50 years for rural drainages and 200 years for urban drainages. GEO (1984) recommends a 200-year return period for the design of surface drainage on man-made slopes.

3 Local Practice in Slope Surface Drainage Designs for Natural Terrain Hazard Mitigation Works under Recent LPMit Projects

The runoff calculations for the drainage designs of six LPMit study areas have been reviewed. These designs were carried out by five local geotechnical consultants and GEO in-house geotechnical engineers respectively. The runoff calculations provide data for the design of storm drains conveying runoff from the outlet of the hillside catchment to the downstream public drainage system. The catchment areas range from 2,500 m^2 to 30,000 m^2.

All the calculations adopted the Rational Method for estimating the surface runoff, the Bransby-Williams equation for estimating the time of concentration and a 200-year return period. A runoff coefficient of 0.4 was used for two study areas (i.e. the lower bound value recommended by DSD (2013) for steep natural slopes) and 1.0 for the remaining four study areas (i.e. the value for man-made slopes recommended by GEO, 1984). No attempt has been made to establish the runoff coefficient based on the proportion of different types of surface cover/ground conditions within the hillside catchments.

Table 3.1 Summary of Design Practice of Surface Drains Adopted in Recent Natural Terrain Hazard Mitigation Works

Location	Catchment Area (m^2)	Rational Method Adopted for Drainage Design	Bransby-Williams Equation Adopted for Time of Concentration	Runoff Coefficient Adopted	Design Return Period (years)
Pa Mei	30,000	Yes	Yes	1	200
Tsing Yi	15,600	Yes	Yes	0.4	200
Evan Count	6,300	Yes	Yes	1	200
Pok Fu Lam	9,500	Yes	Yes	1	200
Sha Tin Height	2,500	Yes	Yes	1	200
Tai Po	10,000	Yes	Yes	0.4	200

Table of Contents
Table of Contents
Table of Contents
Table of Contents

4 WSD Stream Gauge Data

The WSD operates a network of stream flow gauges for water resources planning purpose, and collects stream and catchment yield data from 19 gauging stations in Hong Kong. The sizes of these watersheds range from 0.75 km^2 (at Tsak Yue Wu Upper) to 70 km^2 (at High Island). Data collection commenced in 1945 at three gauging stations at Tai Tam Reservoir, Kowloon Reservoir and Aberdeen Reservoir. By 1979, data collection has been carried out for all the 19 gauging stations.

At each gauging station, a data logger is connected to a float well system to record the water levels in the catchwater at 15-minute intervals. After obtaining the water level records, the flow rates in the catchwater are then determined using a conversion table.

Regular on-site servicing and maintenance of the systems, including inspection of data loggers, changing of batteries and collection of data cards, are carried out once every three weeks. During the inspections, the water level in the catchwater is also measured. If the water level measurement is found to be inconsistent with the record collected by the data logger, calibration of the data logger system and adjustments to the record would be made.

5 Analysis of Four WSD Watersheds

5.1 Characteristics of Watersheds

Stream gauge data collected from four WSD watersheds have been analysed to study the time of concentration, runoff coefficient and peak runoff. These watersheds include Sham Wat, Tai Lam Chung 'A', Tai Lam Chung 'B' and Tsak Yue Wu Upper. Their locations are shown in Figure 5.1. These four watersheds are located within a reasonably close proximity to raingauges. Appendix D gives details, viz. topography and nature of surface cover, of the catchments.

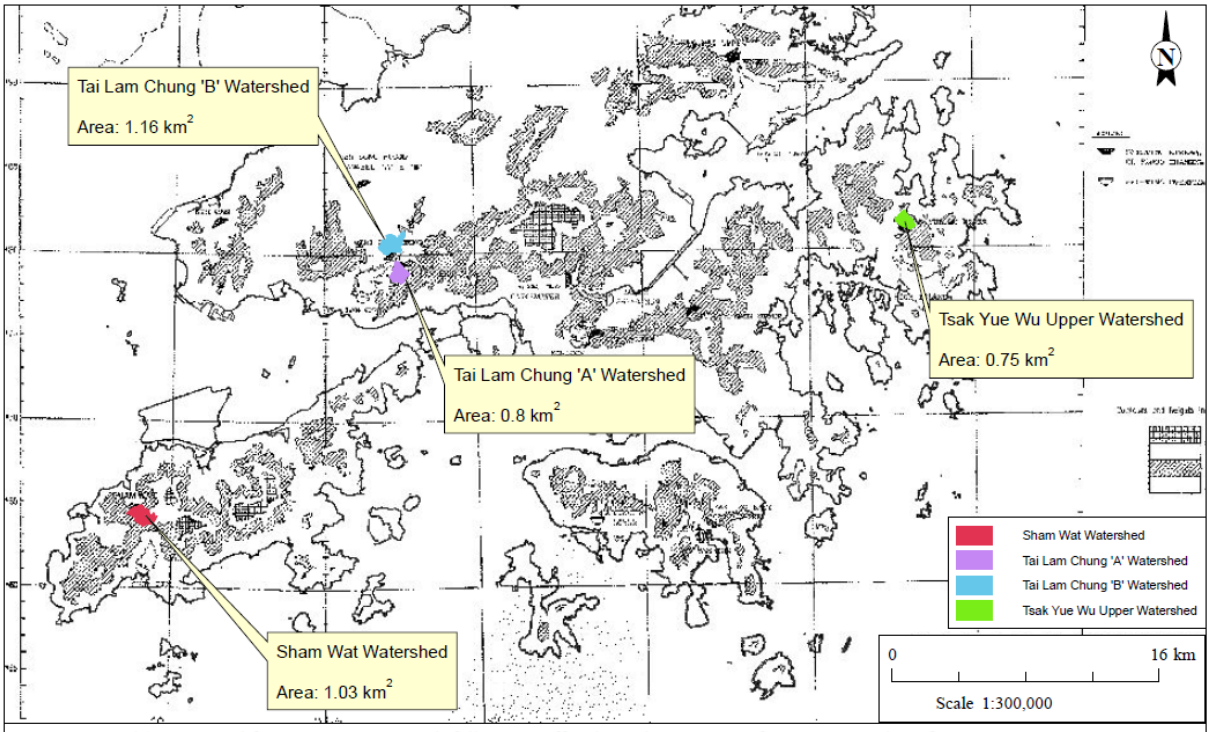
These four WSD watersheds were selected because their catchment areas are comparable to that of a typical natural terrain study catchment in the LPMit Projects (i.e. about 1 km^2). These watersheds, which are located at Lantau (Sham Wat), Sai Kung (Tsak Yue Wu Upper) and Tai Lam (Tai Lam Chung 'A' and 'B'), provide a good geographical spread of the watershed characteristics in Hong Kong.

Tsak Yue Wu Upper involves about 50% rocky ground, Sham Wat and Tai Lam Chung 'A' each involves about 20% rocky ground and Tai Lam Chung 'B' has no rocky ground (Appendix D).

5.2 Time of Concentration of the Four WSD Watersheds

The values of the time of concentration of the four WSD watersheds have been estimated using both empirical equations and hydraulic flow equations. The empirical equations include the Bransby-Williams equation, Kirpich equation, Papadakis and Kazan equation, and Morgali and Linsley equations. The hydraulic flow equations used are the

Table of Contents
Table of Contents
Table of Contents
Table of Contents



Notes: (1) Extracted from "Hong Kong Rainfall & Runoff Vol.28 Plate No.1 Surface Water Station" for Water Year 1991

Figure 5.1 Locations of the Selected Watersheds

wave equation for sheet flows, and Manning's equation for shallow flows and open channel flows. Details of these equations are given in Appendix D.

The above empirical equations and hydraulic flow equations give fairly similar results (see Table 5.1). Taking Sham Wat as an example, the estimated time of concentration is 17.9 minutes by the Bransby-Williams equation, 14.5 minutes by the Kirpich's equation, 14.9 minutes by the Papadakis and Kazan equation, 17.5 minutes by the Morgali and Linsley equation and 17.4 minutes by the hydraulic flow equations. Based on these findings, it appears that the Bransby-Williams equation yields similar results and can be used for the design of local surface drainage for natural terrain.

In the review of the local drainage design practice (Section 3), it is noted that the presence of natural drainage lines was not considered in some of the design calculations. As pointed out in GEO (1984), this could lead to an over-estimation of t_c, and hence under-estimation of the design runoff. GEO (1984) recommends that the time of concentration should be calculated as the sum of (i) the time of travel within the drainage channel (calculated using hydraulic equations), and (ii) the time of concentration for the most remote sub-catchments to the drainage channel (calculated using the Bransby-Williams equation).

Prominent natural drainage channels are observed at the Sham Wat and Tsak Yue Wu Upper watersheds. If the prominent drainage channels are ignored in the calculations (i.e. applying the whole catchment area to the Bransby-Williams equation), the calculated t_c would have been much longer than what it would likely be. Taking Sham Wat as an example, the

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 5.1 Summary of Time of Concentration Estimated by Various Methods

Water-sheds	Empirical Estimation Equations							Time of Concentration Estimated by Hydraulic Flow Equations (min)
	Bransby-Williams				Kirpich	Morgali and Linsley	Papadakis and Kazan	
	Ignoring Prominent Channels		Considering Prominent Channels		Time of Concentration (min)			
	Time of Concentration (min)	Design Rainfall Intensity (mm/min)	Time of Concentration (min)	Design Rainfall Intensity (mm/min)				
Sham Wat	33.8 (over-estimated)	195	17.9 (see Note 1)	250	14.5	17.5	14.9	17.4
Tai Lam Chung 'A'	33.2	195	33.1 (see Note 2)	195	26.7	19.2	22.1	20.3
Tai Lam Chung 'B'	33.4	195	33.4 (see Note 2)	195	33.8	19.5	28.8	30.3
Tsak Yue Wu Upper	26.2	215	14.3 (see Note 1)	270	18.6	14.5	12.1	14.6

Notes:
(1) The Bransby-Williams equation for remote sub-catchments and hydraulic equations for drainage channels within catchment (as recommended by GEO, 1984).
(2) There are no prominent drainage channels in Tai Lam Chung 'A' and Tai Lam Chung 'B'.

estimated time of concentration would become 33.8 minutes instead of 17.9 minutes. If the design return period is taken as 200 years, the design rainfall intensity would be reduced by 22% (from 250 mm/min to 195 mm/min) if the prominent drainage channels in the watersheds are ignored, which is on the un-conservative side.

Attempts have been made to estimate the times of concentration using the WSD gauge data but the results are not definitive due to the constraints of various assumptions made in the analysis. Detailed discussions are given in Appendix D.

5.3 Observed and Design Runoffs at the Four WSD Watersheds

The peak runoffs observed at the four WSD watersheds have been compared with the design peak runoff estimated using the Rational Method. The design runoff has been estimated based on a 1-in-200-year rainfall event. Other assumptions adopted in the estimation are given in Table 5.2.

Table 5.2 Assumptions Adopted in Estimating the Design Peak Runoff

Runoff Coefficient	0.4 or 1.0 (see Section 3)
Time of Concentration	Bransby-Williams equation with drainage channel effect considered
Design Return Period	200 years
Design Rainfall Intensity	From IDF of TGN 30 (GEO, 2011)

The peak runoffs observed each year at the WSD watersheds since installation of the stream gauges are presented in Figures 5.2 to 5.5, on which the design peak runoffs estimated using a storm duration equal to t_c are shown for comparison. The t_c in Sham Wat, Tai Lam Chung 'A', Tai Lam Chung 'B', Tsak Yue Wu Upper are estimated as 18 minutes, 33 minutes, 33 minutes and 14 minutes respectively.

As can be seen in Figures 5.2 to 5.5, when adopting a runoff coefficient of 0.4, storms with return periods of less than 200 years (i.e. 4 to 18 years; the return periods are estimated on the basis of the rainfall duration being taken to be equal to t_c) could have resulted in peak runoffs marginally exceeding the design values corresponding to a 1-in-200-year event. These peak runoffs were observed in 1982 and 2008 at Sham Wat, 1994 at Tai Lam Chung 'A', 1982 at Tai Lam Chung 'B' and 1981 at Tsak Yue Wu Upper. The associated rainfall events (as recorded by nearby rain gauges if available) were not particularly heavy, and the most severe one occurred in 2008 at Sham Wat with an 18-year return period. These rainfall events were much below the design return period of 200 years, suggesting that adoption of a runoff coefficient of 0.4 should have under-estimated the design peak runoffs at these four WSD watersheds. On the other hand, when adopting a runoff coefficient of 1.0, the yearly peak runoffs within the analysis period observed at the four WSD watersheds are all below the design peak runoffs by over 80% on average for the rainstorm experienced over the monitoring period.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

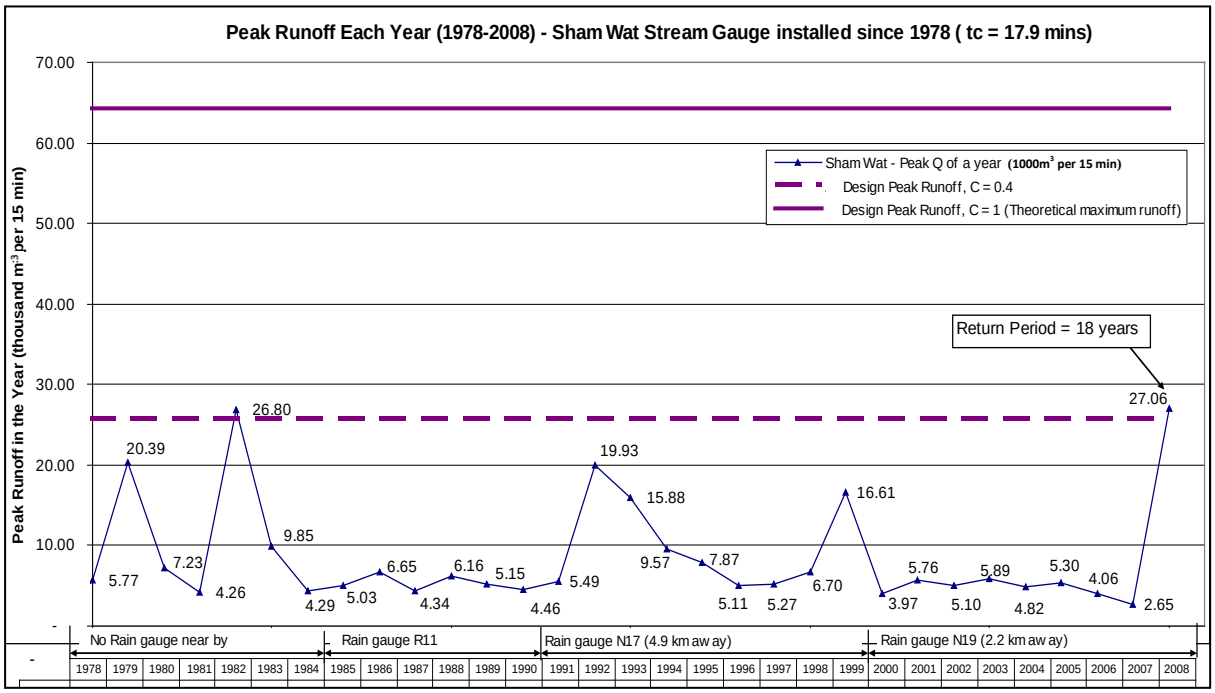


Figure 5.2 Peak Runoffs Observed Each Year at the Sham Wat WSD Watershed

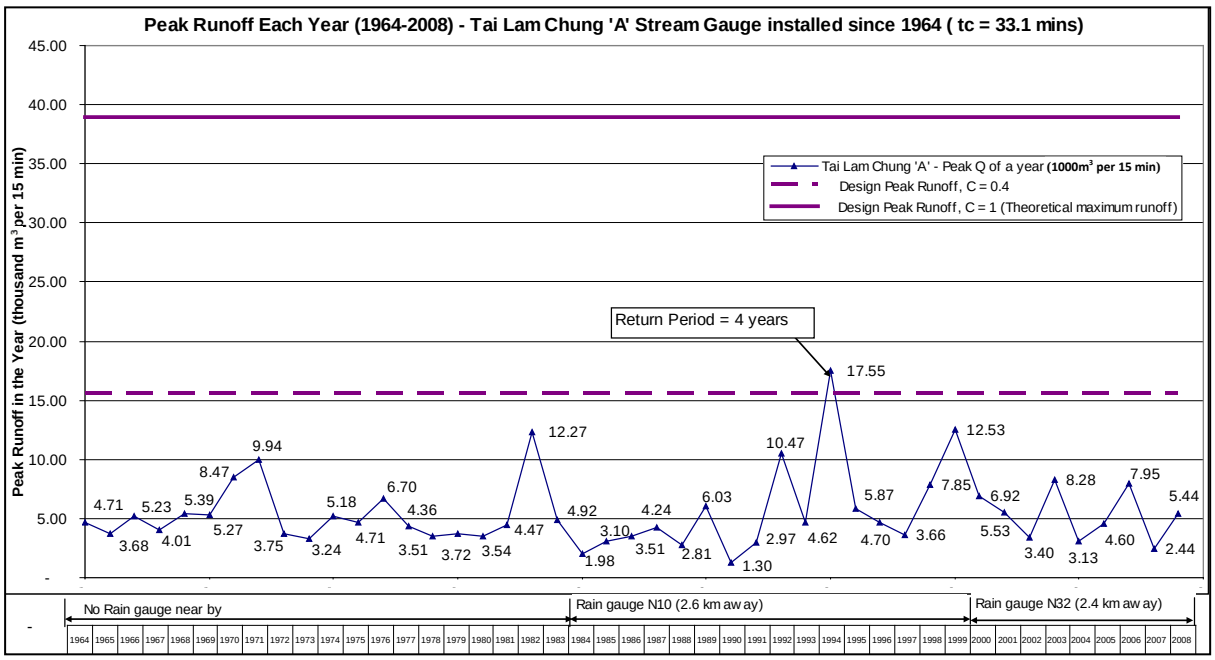


Figure 5.3 Peak Runoffs Observed Each Year at the Tai Lam Chung 'A' WSD Watershed

Table of Contents
Table of Contents
Table of Contents
Table of Contents

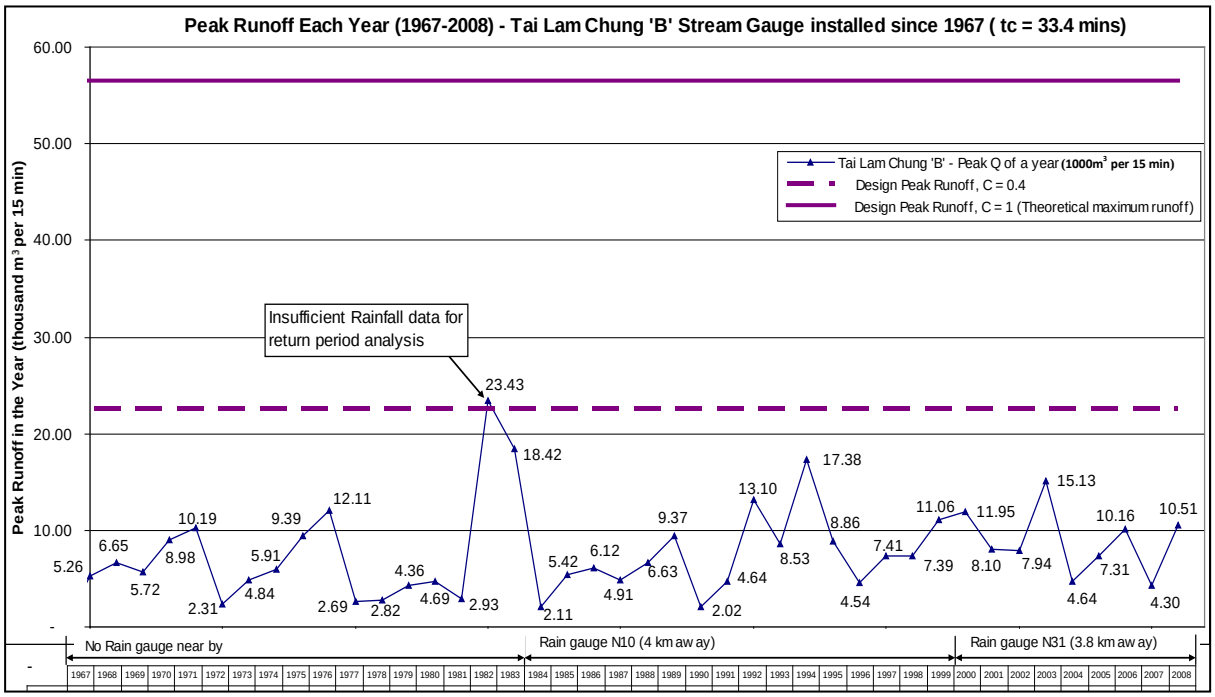


Figure 5.4 Peak Runoffs Observed Each Year at the Tai Lam Chung 'B' WSD Watershed

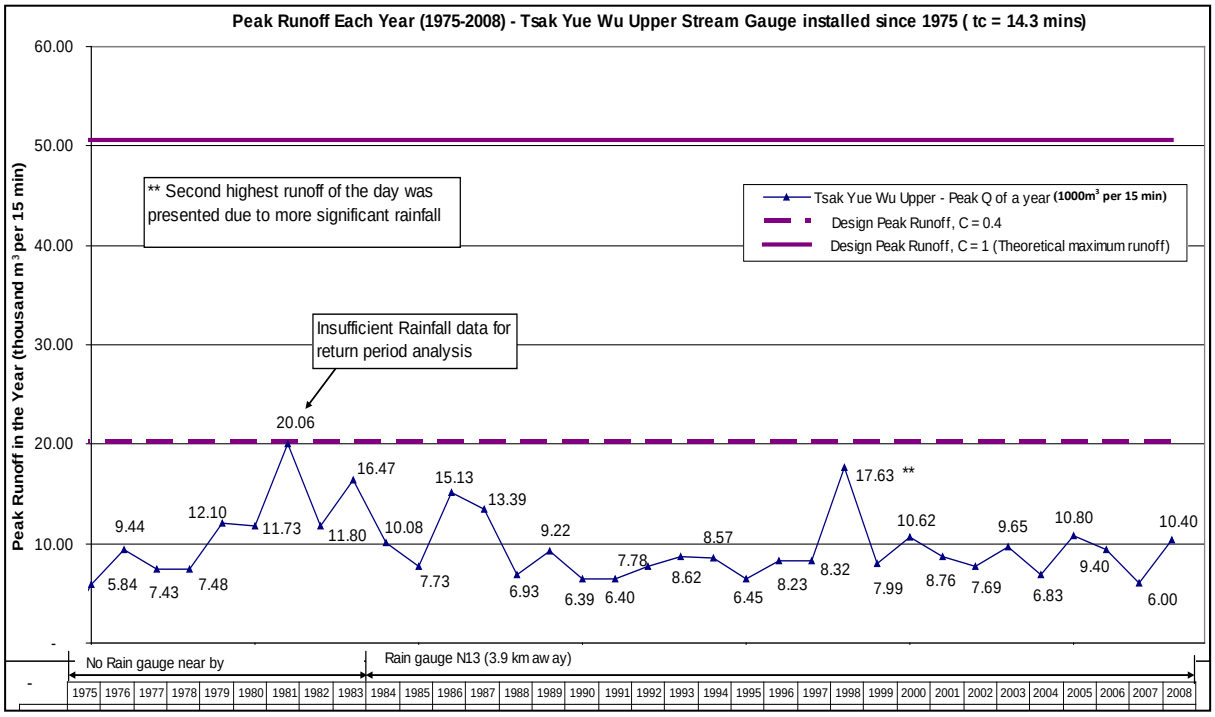


Figure 5.5 Peak Runoffs Observed Each Year at the Tsak Yue Wu Upper WSD Watershed

Table of Contents
Table of Contents
Table of Contents
Table of Contents

5.4 Runoff Coefficients for the Four WSD Watersheds

Runoff coefficients are empirical factors that cannot be determined precisely from the stream gauge data. DSD (2013) recommends a runoff coefficient of 0.4 to 0.9 for steep natural slopes or areas where a shallow soil surface is underlain by an impervious rock layer. However, the criteria on the choice of design value from the recommended range (i.e. 0.4 - 0.9) are not given. As noted from the review of local design practice (see also Section 3), the values of 0.4 and 1.0 had been adopted in the designs selected for review.

Attempts have been made to estimate the runoff coefficient of the four WSD watersheds using the gauge data and the following equation:

$$\text{Runoff Coefficient} = \frac{\text{Steady Runoff}}{\text{Uniform Rainfall} \times \text{Catchment Area}} \quad \ldots\ldots\ldots\ldots\ldots (5.1)$$

This equation is theoretically valid when the amount of runoff becomes steady and this represents the situation when the uniform rainfall duration is longer than the time of concentration of the catchment. In practice, steady runoff could not be reached without a long enough uniform rainfall. As can be seen from Figure 5.6 which shows typical rainfall and runoff patterns at Sham Wat at the time of the peak runoff on 7 June 2008, there was a period of uniform rainfall lasting longer than 20 minutes (which is greater than the estimated time of concentration of about 18 minutes), steady runoff was not yet reached. However, it is considered sufficiently accurate to adopt the peak runoff (which is close enough to the steady runoff given the long preceding uniform rainfall) to estimate the runoff coefficient using equation 5.1 for the present purposes. The average rainfall occurring within 30 minutes (which is longer than the time of concentration preceding the peak runoff) is taken as the uniform rainfall.

Several rainfall events were analysed, including the 2008 rainfall at Sham Wat, the 1994 rainfall at Tai Lam Chung ‘A’, the 2003 rainfall at Tai Lam Chung ‘B’ and the 1998 rainfall at Tsak Yue Wu upper. The 2008 rainfall at Sham Wat and the 1994 rainfall at Tai Lam Chung ‘A’ are associated with record high peak runoff in these watersheds, whereas the 2003 rainfall at Tai Lam Chung ‘B’ and the 1988 rainfall at Tsak Yue Wu Upper are the most severe events with reliable rainfall data during the monitoring period.

5.4.1 Effect of Rocky Ground on Runoff Coefficient

The effect of rocky ground on runoff coefficient has been assessed. Detailed aerial photograph interpretations (API) have been carried out to identify the extent of different types of ground (i.e. rocky ground (impermeable) and permeable ground) in each of the four watersheds. Weighted average runoff coefficients of these watersheds have been calculated based on the proportion of rocky ground and permeable ground identified. Runoff coefficients of 0.9 for rocky ground and 0.4 for permeable ground have been adopted in the calculations following the guidance in DSD (2013).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 5.3 shows the values of the weighted average runoff coefficients for the watersheds. For Sham Wat, where there is about 20% rocky ground, the weighted average runoff coefficient (0.50) matches well with that estimated using WSD's gauge data (0.52).

At Tai Lam Chung 'A', where there is also about 20% rocky ground, the weighted average runoff coefficient (0.51) is about 24% higher than that estimated using WSD's gauge data (0.39).

Tai Lam Chung 'B' has no rocky ground and the assumed runoff coefficient 0.4 is slightly higher than that estimated using WSD's gauge data (0.34).

At Tsak Yue Wu Upper, where there is about 50% rocky ground, the weighted average runoff coefficient (0.65) matches quite well with that estimated using WSD's gauge data (0.61).

In summary, the weighted average runoff coefficients are in reasonable agreement with the runoff coefficients estimated using the WSD's gauge data at Sham Wat and Tsak Yue Wu Upper, but are slightly higher than those estimated using WSD's gauge data at Tai Lam Chung 'A' and 'B'.

In terms of peak runoff, it could have been under-estimated by as much as 63% at Tsak Yue Wu Upper should the effect of rocky ground be ignored in the drainage design (i.e. adopting a runoff coefficient of 0.4).

Table 5.3 Effect of Rocky Ground on Runoff Coefficients

Location	Ground Condition[1]	Weighted Average Runoff Coefficient (rocky ground = 0.9 permeable ground = 0.4) [2]	Runoff Coefficient Estimated from WSD's Gauge Data (see Table 5.4)	Possible Underestimation in Design Peak Runoff (using runoff coefficient of 0.4 instead of the weighted average coefficients)
Sham Wat	rocky ground 20% permeable ground 80%	0.50	0.52	25%
Tai Lam Chung 'A'	rocky ground 21% permeable ground 79%	0.51	0.39	27%
Tai Lam Chung 'B'	rocky ground 0% permeable ground 100%	0.40	0.34	0%
Tsak Yue Wu Upper	rocky ground 49% permeable ground 51%	0.65	0.61	63%

Notes: (1) See Appendix D.
(2) Runoff Coefficients recommended by DSD (2013).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

5.4.2 Effect of Antecedent Rainfall on Runoff Coefficient

A typical runoff/rainfall graph around the time of the peak runoff (at Sham Wat on 7 June 2008) is given in Figure 5.6. As can be seen in this figure, the total runoff could be a combination of the immediate runoff and baseflow (see Figure 2.1).

The runoff coefficients estimated using equation 5.1 and the peak runoff observed in the four watersheds are given in Table 5.4. The runoff coefficients ranged from 0.34 to 0.61 when the baseflows due to antecedent rainfall were not taken into consideration. The runoff coefficients increased from 0.41 to 0.79 when the baseflows due to antecedent rainfall were included in the estimation. The surface runoff was noted to have increased ranging from 21% (at Tai Lam Chung 'B') to 44% (at Tai Lam Chung 'A') due to antecedent rainfall (see Table 5.4). The average increase in surface runoff due to antecedent rainfall among the four watersheds is about 31%.

Assuming there was a 10% increase in surface runoff on rocky ground due to antecedent rainfall (i.e. *C* increases from 0.9 to 1.0), the surface runoff in permeable ground would increase by 11% (at Tai Lam Chung 'A') to 50% (at Sham Wat) due to antecedent rainfall, with an average of 33%. Amongst the four watersheds, the values of *C* of permeable ground of two watersheds (Sham Wat and Tsak Yu Wu Upper) show an increase of approximately 50%.

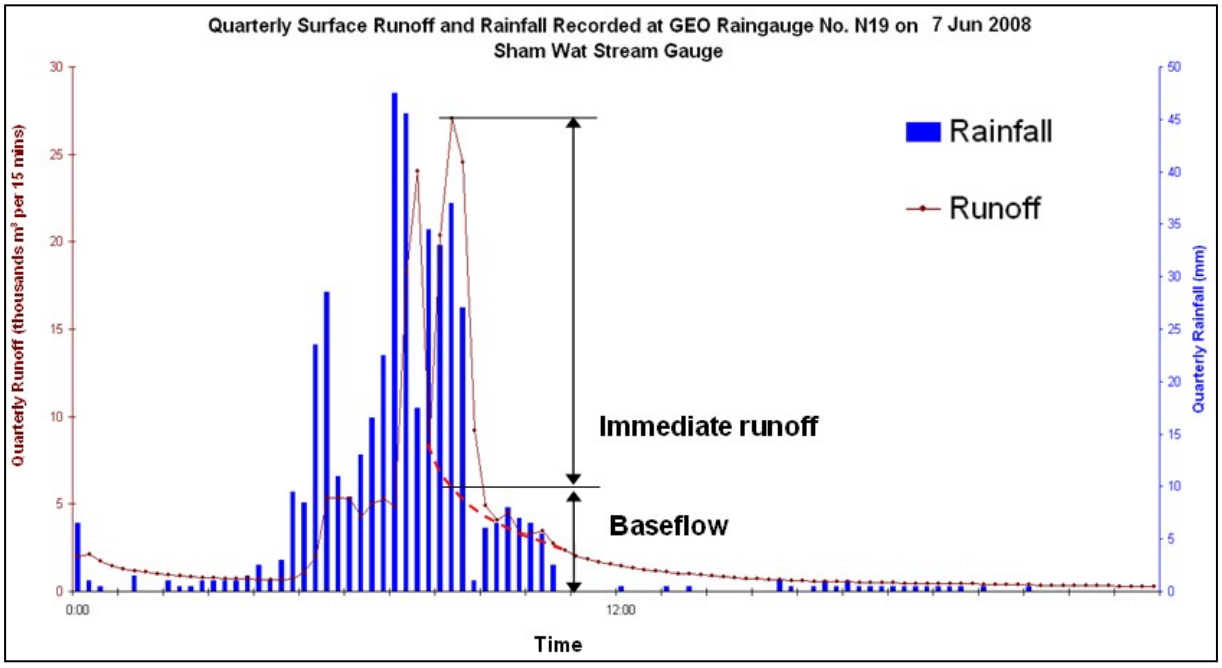


Figure 5.6 Typical Runoff and Rainfall Patterns Observed at the Time of the Peak Runoff (on 7 June 2008 at Sham Wat)

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 5.4 Effect of Antecedent Rainfall on Runoff Coefficient

Location (year concerned)	Runoff Coefficient, *C* Estimated from WSD's Gauge Data		Increase in Runoff Coefficient Due to Antecedent Rainfall	% of Rocky Ground	Assumed Runoff Coefficient in Rocky Ground Due to Antecedent Rainfall[(1)]	% of Permeable Ground	Estimated % Increase in Runoff Coefficient in Permeable Ground Due to Antecedent Rainfall
	Discounting Baseflow Due to Antecedent Rainfall	Including Baseflow Due to Antecedent Rainfall					
Sham Wat (2008)	0.52	0.68	+ 0.16 (+31%)	20%	1.0	80%	+50%[(2)]
Tai Lam Chung 'A' (1994)	0.39	0.56	+ 0.17 (+44%)	21%	1.0	79%	+11%[(2)]
Tai Lam Chung 'B' (2003)	0.34	0.41	+ 0.07 (+21%)	0%	1.0	100%	+21%
Tsak Yue Wu Upper (1998)	0.61	0.79	+ 0.18 (+30%)	49%	1.0	51%	+48%[(2)]
						Average	= 33%

Notes:
(1) Assume *C* in rocky ground increases from 0.9 to 1.0 due to antecedent rainfall.
(2) This value corresponds to the calculated weighted average runoff coefficient matching the value of *C* estimates from WSD's gauge data, assuming that *C* of permeable ground is 0.4.

5.5 Observed and Design Runoffs at the Four WSD Watersheds Using Enhanced Coefficients of Runoff

As discussed in Section 5.4, the effects of rocky ground and antecedent rainfall on runoff coefficient could be significant. It is suggested that the runoff coefficient should be determined with due regard to the actual extent of rocky ground and permeable ground by means of API or other appropriate methods. Taking cognizance of the uncertainties involved, it is suggested that the runoff coefficient estimated in this way should be increased to 1.0 for rocky ground and by 50% for permeable ground in order to cater for the effect of antecedent rainfall. This suggested increase in *C* for permeable ground is 17% greater than the average increase observed in the four watersheds. Table 5.5 summarises the suggested parameters to be adopted in assessing the design peak runoff.

Using the above parameters, runoffs of a 200-year return period rainfall event in the four WSD watersheds have been estimated and shown in Table 5.6. These runoffs can provide reasonable estimates which envelope the peak runoffs measured in these watersheds. Details of the comparison can be found in Appendix E.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 5.5 Suggested Parameters for Assessing Design Peak Runoffs

Runoff Coefficient (Effects of relative proportions of rock ground and permeable ground)	Use weighted average coefficient be reference to the respective areas of different ground conditions (0.9 for rocky ground and 0.4 for permeable ground)
Time of Concentration	Use Bransby-Williams equation considering the presence of prominent drainage channels
Antecedent Rainfall	*C* increased to 1.0 for rocky ground and increased by 50% for permeable ground
Design Return Period	200 years
Design Rainfall Intensity	From IDF of TGN 30 (GEO, 2011)

Table 5.6 Observed and Reassessed Design Peak Runoffs with 200-year Return Period Estimated Using Runoff Coefficients Adjusted for Effects of Antecedent Rainfall and Presence of Rocky Ground

Location	Highest Peak Runoff Observed (1000 m^3 per 15 min)	Rainfall Depth (rainfall duration)	Rainfall Return Period	Time of Concentration (t_c) & Weighted Average Runoff Coefficient (*C*)	Value of *C* with Adjustment for Antecedent Rainfall Effects	Design Peak Runoff (1 in 200 years) with Increases in *C* for Rocky Ground and Antecedent Rainfall Effects (1000 m^3 per 15 min)
Sham Wat	27.06 (in 2008)	51 mm (20 min)	17.5 years	t_c = 17.9 min *C* = 0.50	0.68	41.84
Tai Lam Chung 'A'	17.55 (in 1994)	54 mm (30 min)	4.0 years	t_c = 33.1 min *C* = 0.51	0.68	25.60
Tai Lam Chung 'B'	15.13 (in 2003)	66 mm (30 min)	14.3 years	t_c = 33.4 min *C* = 0.40	0.6	29.41
Tsak Yue Wu Upper	17.63 (in 1998)	37 mm (15 min)	8.3 years	t_c = 14.3 min *C* = 0.65	0.80	40.77

Table of Contents
Table of Contents
Table of Contents
Table of Contents

6 Discussions and Recommendations

6.1 Surface Runoff Estimation Models

As discussed in Section 2.2.1, the Rational Method is by far the most commonly used method worldwide for estimating surface runoff of small catchment areas of less than 0.8 km^2 to 10 km^2.

Other methods, such as the Curve Number (CN) method, hydrograph method and statistical runoff models, are widely used in North America. However, these methods, which require the establishment of various location-specific empirical relationships between meteorological and surface hydrological parameters, are not commonly adopted in other places. On the other hand, the Rational Method has been adopted prevailingly in local practice for many years and appears to have yielded reasonable estimates of the surface runoff based on field data. It is considered appropriate to continue with the use of the Rational Method for estimation of surface runoff from natural terrain for drainage design in LPMit projects.

6.2 Time of Concentration

The time of concentration as estimated by the Bransby-Williams equation (Section 5.2 and Table 5.1) for the four WSD watersheds compare reasonably well with that estimated by other methods commonly used worldwide. The Bransby-Williams equation is simple to use and it yields reasonable time of concentration for the design of surface drainage.

However, care must be exercised in ensuring the appropriate use of the Bransby-Williams equation. As pointed out by GEO (1984), when prominent drainage channel exists within a catchment, the time of concentration should be calculated by adding the time of travel within the drainage channel (estimated using hydraulic flow equations) to the time of concentration calculated within the remote sub-catchments to the drainage channel (estimated using the Bransby-Williams equation). The findings of the present review indicate that the peak runoff could be under-estimated by as much as 22% (at the Sham Wat watershed) when prominent drainage channels are ignored in the design calculations (see Section 5.2).

Hydraulic flow equations could be used to estimate the time of concentration in catchments where the ground profiles are complicated or where the catchment is large. Hydraulic flow equations could take care of the effects arising from sheet flows, shallow concentrated flows or open channel flows.

6.3 Runoff Coefficient

The review of the drainage design calculations for the six study areas (see Section 3) indicates that some local practitioners have adopted a runoff coefficient of 0.4 (the lower bound value recommended by DSD (2013)) whilst others have adopted a value of 1.0 for the design of surface drains on natural terrain under the LPMit Programme. Adoption of a runoff coefficient of 0.4 could have under-estimated the design peak runoffs on natural terrain (see Section 5.3).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Attempts have been made to estimate the runoff coefficients of the four WSD watersheds using a weighted average runoff coefficient, where the runoff coefficient of rocky ground was taken as 0.9 and permeable ground as 0.4 (see Section 5.4.1). The weighted average runoff coefficients match reasonably well with the runoff coefficients estimated using WSD's gauge data at Sham Wat and Tsak Yue Wu Upper, but are slightly higher than those estimated using WSD's gauge data at Tai Lam Chung 'A' and 'B'. The peak runoff could have been under-estimated by as much as 63% (at Tsak Yue Wu Upper) should the effect of rocky ground be ignored. As far as practicable, it is considered reasonable to adopt the weighted average runoff coefficient approach (e.g. *C* value for rocky ground = 0.9 and *C* value for permeable ground = 0.4) for steep catchments with rocky ground.

In addition, the effect of antecedent rainfall should be allowed for in the estimation of runoff coefficient for a more robust design. As discussed in Section 5.4.2, the increase in surface runoff due to antecedent rainfall alone could be as high as 44% (at Tai Lam Chung 'A') and the average value among the four watersheds is 31%. Assuming that the increase in the runoff coefficient due to antecedent rainfall in rocky ground is increased to 1.0 (from 0.9), the additional runoff due to antecedent rainfall in permeable ground could be as high as 50%. Hence, when the effect of antecedent rainfall is considered in the drainage design, the value of runoff coefficient in rocky ground should be taken as unity (1.0) and an increase of 50 % in the value of runoff coefficient for permeable ground is recommended.

It should be noted that the above recommendations are subject to constraints, as they are largely based on the runoff characteristics observed in only four local watersheds. The recorded rainfall in these four watersheds over the monitoring period was not particularly severe (with a maximum return period of 18 years) and the site settings may not be particularly adverse. The potential siltation in the drainage provisions has also not been considered. Therefore, further increase in the value of runoff coefficient should be made where deemed necessary by designers.

6.4 Recommended Approaches for Estimation of Surface Runoff

It is recommended that the following approaches should be adopted for estimating surface runoff from natural terrain catchments.

(a) Surface runoff estimation model: The Rational Method should be adopted.

(b) Time of concentration (t_c): The Bransby-Williams equation, with due consideration of any prominent natural stream channels (with the use of hydraulic equations), should be used for determining the time of concentration.

(c) Runoff coefficient (*C*): Weighted average runoff coefficient to account for the relative proportions of different ground conditions (e.g. steep natural soil slopes, areas of soil surface underlain by shallow rock layer, etc.) should be established. The values of *C* for different

Table of Contents
Table of Contents
Table of Contents
Table of Contents

ground conditions as recommended by DSD (2013) should be adopted for determining the weighted average runoff coefficient. In considering the effects of antecedent rainfall, the value of *C* for area underlain by shallow rock layer should be taken as unity and an increase of 50% should be allowed for in the *C* value for permeable ground conditions. The increased value of *C* due to antecedent rainfall should be capped at 1.0.

(d) Rainfall intensity: The rainfall intensity should be assessed based on the IDF curves given in TGN 30 (GEO, 2011), with a 200-year return period for slope drainage design.

A worked example illustrating the use of the recommended approaches for estimating the design peak runoff is given in Appendix F.

6.5 Further Work

The gauge data collected at the four WSD watersheds have provided invaluable information for the analyses in the present review. The flow data are collected at 15-minute intervals while the rainfall data are captured every 5 minutes by GEO and every 1 minute by the Hong Kong Observatory. To further enhance the understanding of the rainfall/runoff relationship, measurements of the runoff discharge at a higher frequency would be beneficial.

Use of physical models may also be considered as an alternative method for runoff estimation. Numerical modelling using computer programs (e.g. MIKE-SHE) may be carried out for some of the WSD watersheds and the computer output compared with the gauge data. However, this approach may be subject to constraints as most of the input parameters required (e.g. evaporation rates, infiltration rates, soil layering and properties, bedrock levels and overland Manning coefficients) are not readily available for typical natural terrain in Hong Kong.

7 Conclusions

This Study has reviewed the commonly-used estimation methods of surface runoff on natural terrain and examined selected WSD stream gauge data to investigate the time of concentration and effects of ground cover and antecedent rainfall on the runoff coefficient for estimating surface runoff using the Rational Method.

Recommendations pertaining to the determination of time of concentration and runoff coefficient for runoff estimation of natural terrain have been made.

Table of Contents
Table of Contents
Table of Contents

8 References

DSD (2000). *Stormwater Drainage Manual - Planning, Design and Management*. Drainage Services Department, Hong Kong, 130 p.

DSD (2003). *Design of Stormwater Inlets (version 2) (Practice Note. 1/2003)*. Drainage Services Department, Hong Kong, 27 p.

DSD (2013). *Stormwater Drainage Manual (with Eurocodes incorporated) - Planning, Design and Management*. Drainage Services Department, Hong Kong, 172 p.

GEO (1984). *Geotechnical Manual for Slopes (Second Edition)*. Geotechnical Engineering Office, Hong Kong, 302 p. (Reprinted, 2011)

GEO (2011). *New Intensity-Duration-Frequency Curve for Slope Drainage Design (Technical Guidance Note No. 30*). Geotechnical Engineering Office, Hong Kong, 4 p.

Tang, C.S.C. & Cheung, S.P.Y. (2007). *Review of Surface Drainage Design (Discussion Note 1/2007*). Geotechnical Engineering Office, Hong Kong, 22 p.

WPCF (1963). *Design and Construction of Sanitary and Strom Sewers (WPCF Manual of Practice No. 9)*. Water Pollution Control Federation, Washington, D.C., 283 p.

Appendix A

Brief Account of Publications (Other Than Stormwater Drainage Manual and Geotechnical Manual for Slopes) on Surface Runoff Estimation

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

Table of Contents
Table of Contents
Table of Contents

A.1 Introduction

Local guidelines for the design of surface drainage in Hong Kong are given in various publications. The most commonly used ones are the Stormwater Drainage Manual (DSD, 2000) by DSD and the Geotechnical Manual for Slopes (GEO, 1984) by the Geotechnical Engineering Office (GEO). A brief account of these two publications on surface runoff estimation for drainage design in Hong Kong is provided in Section 2.1 of the main text. A brief account of other publications in Hong Kong on surface runoff estimation is given in this Appendix.

A.2 Technical Report No. 6 - Stormwater Drainage Design in Hong Kong (Tin, 1969)

Technical Report No. 6 (TR6) issued by the Drainage Works Division of the Public Works Department in 1969 (Tin, 1969) is one of the earliest guidelines in Hong Kong on the estimation of surface runoff for stormwater drainage.

Tin (1969) reviewed two methods available for the design of stromwater drainage in Hong Kong at that time, namely the Wilmot-Morgan Method and the Development Division Method, both of which are Rational Method, which can be expressed mathematically as follows:-

$$Q = CiA \quad \text{.....} \quad \text{(A.1)}$$

where Q = maximum runoff (volume of water per unit time)
i = design mean intensity of rainfall (rain depth per unit time)
A = area of catchment
C = runoff coefficient (dimensionless)

Tin (op cit) recommended using the Rational Method for practical design of stormwater drainage, as it was simple and straightforward to use. Also, modified Bransby-Williams equation was recommended for evaluation of the time of concentration. This report suggested a design return period ranging from 10 years (from unimportant land drainage) to 200 years (for nullah and main stormwater pipe). The use of runoff coefficient of 1.0 for all cases except for unimportant land drainage where runoff coefficient could be 0.8 was suggested.

A.3 Road Note 6 - Road Note on Road Pavement Drainage and Guidance Notes on Road Pavement Drainage Design (HyD, 1994 & 2010)

Road Note 6 was first published by the Highways Department in 1983 providing methods for drainage design on roads based on Transport Research Laboratory Reports Nos. LR277, LR602 and CR2. The Note was later updated in 1994 (HyD, 1994) and is now superseded by Guidance Notes on Road Pavement Drainage Design issued in 2010 (HyD, 2010). These Guidance Notes have included the latest information and findings from extensive full scale testing carried out in Hong Kong.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

HyD (2010) recommends a design return period of 1 in 50 years (with a minimum factor of safety of 1.2) for the ultimate limit state and 2 per year for the serviceability limit state. The rainfall duration is taken as 5 minutes, resulting in a design rainfall intensity of 270 mm/hr for the ultimate limit state and 120 mm/hr for the serviceability limit state.

A.4 Highway Slope Manual (GEO, 2000)

The Highway Slope Manual (GEO, 2000) recommends a standard of good practice on slope engineering that involves highway slopes and their maintenance. It does not provide further guidance on the design of slope surface drainage but refers to Chapter 8 of GEO (2000) for guidance.

GEO (2000), however, provides examples of locations which may be considered as critical with regard to the impact of drainage on stability of highway slopes. GEO (2000) recommends that gullies and buried drainage facilities including pipes and cross road drains/culverts should be generously provided at the critical locations, to ensure that water will not overflow onto the road level in the case of these drainage facilities being partially blocked (with say only 50% of the design capacity remaining). The containment of road surface runoff at the critical locations should also be enhanced, for example, by the provision of upstand wall or channels with an upstand along the crest of the downhill slopes.

A.5 GEO Reports, Technical Guidance Notes and Discussion Notes

Over the years, GEO has reviewed and updated the design guidelines for surface drainage on man-made slopes through GEO reports, Technical Circulars, Technical Guidance Notes and Discussion Notes.

Premchitt et al (1995) evaluated the effectiveness of various types of slope surface cover (chunam, grass and grass with shrubs and trees) in generating rainstorm runoff. The study measured rainfall and surface runoff on seven slopes between 1986 and 1988. The runoff coefficient for slope surface covered with vegetation was found to vary between 0.3 and 0.5, and about 0.9 for chunamed slope surface.

Wong & Ho (1996) presented some thoughts on the assessment and interpretation of rainfall return period with consideration of probability and statistics.

Evans & Yu (2001) presented the results of extreme-value analyses of rainfall data obtained from 46 rain-gauges throughout Hong Kong between 1984 and 1996. The study examined whether these results were consistent with the values calculated indirectly using the other techniques and made recommendations on the use of these results.

Tang & Cheung (2007) discussed some problems on the design and detailing of surface drainage system and suggested some areas worth investigation.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

GEO (2011) reviewed the latest rainfall data and promulgated a set of new intensity-duration-frequency (IDF) curves to supersede the IDF curves given in Figure 8.2 of GEO (1984).

A.6 References

DSD (2000). *Stormwater Drainage Manual - Planning, Design and Management*. Drainage Services Department, Hong Kong, 130 p.

DSD (2013). *Stormwater Drainage Manual (with Eurocodes incorporated) - Planning, Design and Management*. Drainage Services Department, Hong Kong, 172 p.

Evans, N.C. & Yu, Y.F. (2001). *Regional Variation in Extreme Rainfall Value (GEO Report No. 115*). Geotechnical Engineering Office, Hong Kong, 81 p.

GEO (1984). *Geotechnical Manual for Slopes (Second Edition).* Geotechnical Engineering Office, Hong Kong, 302 p. (2011 Reprinted)

GEO (2000). *Highway Slope Manual*. Geotechnical Engineering Office, Hong Kong, 114 p.

GEO (2011). *New Intensity-Duration-Frequency Curve for Slope Drainage Design (Technical Guidance Note No. 30*). Geotechnical Engineering Office, Hong Kong, 4 p.

HyD (1994). *Road Pavement Drainage (Road Note 6)*. Research & Development Division, Highways Department, Hong Kong, 32 p.

HyD (2010). *Notes on Road Pavement Drainage Design*. Research & Development Division, Highways Department, Hong Kong, 39 p.

Premchitt, J., Lam, T.S.K., Shen, J.M. & Lam, H.F. (1995). *Rainstorm Runoff on Slope (GEO Report No. 12).* Geotechnical Engineering Office, Hong Kong, 211 p.

Tang, C.S.C. & Cheung, S.P.Y. (2007). *Review of Surface Drainage Design (Discussion Note 1/2007*). Geotechnical Engineering Office, Hong Kong, 22 p.

Tin, K.Y. (1969). *Stormwater Drainage Design in Hong Kong (Technical Report No. 6).* Drainage Works Division, Civil Engineering Office, Public Works Department, Hong Kong, 20 p.

Wong, H.N. & Ho, K.K.S. (1996). *Thoughts on the Assessment and Interpretation of Return Periods of Rainfall (Discussion Note 2/96).* Geotechnical Engineering Office, Hong Kong, 19 p.

Appendix B

Commonly Used Methods in Estimating Surface Runoff

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

B.1 Introduction

Surface runoff resulting from rainfall depends on many factors, such as rainfall intensity and spatial and temporal characteristics, surface cover, subsurface soils and their hydraulic characteristics, antecedent moisture condition, watershed area and topography. Surface runoff estimation methods vary in complexity and data needs. In general, surface runoff can be estimated using a design rainfall intensity/profile and rainfall-runoff relationships. Some of these estimation methods are only applicable to gauged watersheds. Some methods are used only for estimating peak flow rate for designing drainage distribution elements. Some methods also consider temporal characteristics and estimate flow volume for designing the capacity of storage elements. Most methods do not include baseflow, throughflow, or subsurface return flow. Baseflow is the delayed discharge in the catchment derived from underground water stored in the land due to antecedent rainfall events. Throughflow is the horizontal movement of water in the soil zone which emerges on land before it enters a body of surface water. Subsurface return flow is the water returning to the land surface at a lower elevation under the force of gravity or gravity-induced pressures. It is a very slow flow that can remain in aquifers for a long period of time.

Choice of an estimation method depends on the purpose of the runoff estimation exercise, time scale, size of the area of concern, ease of use, data needs, and local practice. The more common approaches adopted in engineering design include the Rational Method, Curve Number (CN) method and hydrograph method. Engineers also use time-area method, regression method, statistical data analysis and numerical modeling. Section B.2 describes the Rational Method, the extension of the Rational Method to time-area method and the modified Rational Method. The framework and key elements of the curve number method are presented in Section B.3. The hydrograph method, which addresses the temporal aspect and flow volume, is discussed in Section B.4. Highlights of the reservoir routing method, statistical analysis of gauge data method and regression method are provided in Sections B.5 to B.7. Some of the research and development work in surface runoff estimation is discussed in Section B.8. Section B.9 discusses advanced computer software for modeling the rainfall-runoff process.

B.2 Rational Method

The Rational Method was used as far back as the mid-nineteenth century (Mulvaney, 1851). It continues to be the most commonly used rainfall-runoff analysis framework (e.g. Chow et al, 1988; Bedient & Huber, 1992; Linsley et al, 1986) for design because of its simplicity. It computes peak direct runoff instead of runoff hydrograph. The key concept of this method is the assumption that uniform rainfall over time and space produces a steady peak runoff after the water from all parts of the watershed has reached the runoff location considered. The time for water in the watershed to travel from the hydraulically most distant point in the contributing drainage catchment to the runoff location under consideration is referred to as the time of concentration.

The original form of the Rational Method considers uniform rainfall intensity over time and space. The peak flow rate at a point of concern in the drainage system is computed by:

Table of Contents Table of Contents Table of Contents Table of Contents

$$Q = CiA \quad \text{.....} \quad \text{(B.1)}$$

where Q = maximum runoff (volume of water/unit time)
i = rainfall intensity (rainfall depth/unit time)
A = tributary area of watershed to the runoff considered
C = runoff coefficient (dimensionless)

The runoff coefficient is a function of land use. If land use within the area is non-uniform, it is a common practice to use an equivalent runoff coefficient computed by area-weighted averaging.

In a statistical framework, rainfall intensity depends on the risk level (return period) considered and rainfall duration, as typically represented by an intensity-duration-frequency (IDF) relationship. It is assumed that the maximum peak runoff occurs when the rainfall intensity corresponds to a rainfall event with a duration equal to the time of concentration. The time of concentration equals to the sum of the inlet time and flow time, i.e., the longest total travel time for water to reach the drainage network and then flow to the runoff location considered. It is a function of the characteristics of the area of concern, such as topography, land use, and geometry. It is difficult to measure time of concentration. It is commonly estimated using published empirical relationships based on basin characteristics. Many such empirical formulas are available, such as Kirpich (1940) and Izzard (1946). Alternatively, it can be computed by hydraulic flow methods, such as kinematic wave equation for overland flow.

Due to the simplified assumptions, the application of the Rational Method is generally limited to a small area without the presence of significant flow variation within the area. Various agencies have different practices in using the Rational Method, concerning watershed size that the method can be used, selection of runoff coefficients, risk level to be considered, time of concentration estimation method, Intensity-Duration-Frequency (IDF) characteristics, etc. Some agencies set a maximum limit on time of concentration. Many engineers assume that the entire drainage area is the value to be entered in the Rational Method equation. If the drainage area is an irregular shape, it is possible that a portion of the area having a shorter time of concentration can lead to a greater runoff rate than the runoff rate calculated for the entire area which has a longer time of concentration. Similarly, a portion of a drainage area with a higher C value than the rest of the area may produce greater runoff than that calculated for the entire area. In some cases, the calculated runoff from interconnected impervious sub-areas yields the larger peak runoff than that for the entire area.

The time-area method can be regarded as an extension of the Rational Method concept to non-uniform rainfall and irregular areas (e.g., Bedient & Huber, 1992). The product of C and i in the rational formula can be considered as equivalent to the excess rainfall that contributes to the runoff. The rainfall hyetograph is discretised into time intervals with uniform rainfall within each interval. The area of the region contributing to the runoff during each time interval is estimated from isochrones of equal time (assuming constant and uniform effective rainfall) to the runoff location of concern (time-area histogram). The runoff can be estimated by summing the contribution from rainfall during each time interval:

Table of Contents
Table of Contents
Table of Contents
Table of Contents

$$Q = \sum RA \quad \text{.....} \quad (B.2)$$

where Q = Runoff
R = excess rainfall
A = tributary area corresponding to time interval

The modified Rational Method is an extension of the Rational Method for rainfall lasting longer than the time of concentration for developing hydrographs for storage design (e.g., Chow et al, 1988). The resulting hydrograph is trapezoidal with the duration of rising and recession limbs equal to the time of concentration. The peak runoff is computed using the rainfall intensity corresponding to the rainfall duration considered. If the rainfall duration is the same as the time of concentration, the trapezoidal hydrograph becomes triangular.

B.3 Curve Number Method

The Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) developed the Curve Number (CN) method for estimating direct runoff depth. The SCS became the current Natural Resources Conservation Service (NRCS) in 1994. The CN method has been widely used in the U.S. for about 50 years. Some countries have adopted the concept of the CN method and have implemented various adaptations. The CN method is implemented in many commonly used hydrologic models, such as TR-20, TR-50, SWMM and HEC-HMS.

The CN method requires basic data similar to that used in the Rational Method. However, it considers hydrologic responses in more details, such as the time distribution of rainfall, initial rainfall losses to interception and depression storage, and infiltration rate that decreases during the course of a storm. The concept behind the CN method involves two assumptions. The first assumption is that runoff (Q) does not start until the rainfall volume (P) reaches a quantity referred to as the initial abstraction (I_a), which represents the total water volume of interception, depression storage and infiltration. As runoff starts, part of the rainfall is lost to actual retention (F). As rainfall continues, actual retention increases to a maximum value referred to as the potential maximum retention (S). The ratio of actual retention to potential maximum retention is empirically assumed to be the same as the ratio of actual runoff to potential maximum runoff. The SCS runoff equation is expressed as:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{.....} \quad (B.3)$$

Based on regression using rainfall and runoff data, SCS (1964 & 1972) assume that initial abstraction is equal to 20% of the potential maximum retention (i.e. $I_a = 0.2S$). Values less than 20% have subsequently been reported in published literatures. The resulting runoff equation becomes:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{.....} \quad (B.4)$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The potential maximum retention is converted into *CN* based on the following transformation when it is expressed in English units:

$$CN = \frac{1000}{10 + S} \quad \text{.....} \quad \text{(B.5)}$$

That is

$$S = 10(\frac{100}{CN}) - 1 \quad \text{.....} \quad \text{(B.6)}$$

As a result, the value of *CN* ranges from 0 (for infinitely large S) to 100 (when $S = 0$). The transformation allows the rainfall-runoff relationship to be linearly interpolated with respect to the *CN*. Infiltration after runoff started is the major contribution to the potential maximum retention. Thus, *CN* is selected based on land use, land treatment, hydrologic condition, soil group and antecedent soil moisture condition. For non-uniform basins, weighted averaged *CN* can be used. All soils are grouped into four basic groups depending on the minimum infiltration capacity, and based on laboratory tests and soil texture. The four groups are A, B, C and D, with sands in group A and clays in group D. This hydrologic classification system is a major component of the runoff Curve Number system for classification of hydrologic sites, and it is noted that this classification system is not commonly used for geotechnical classification of soils in slope engineering in Hong Kong.

For a selected return period, rainfall intensity is a function of rainfall duration. The SCS published several design dimensionless rainfall distributions. The CN method can be applied to estimate the runoff volume for various rainfall durations. Alternatively, the CN method can be used to estimate the temporal profile of runoff corresponding to a design rainfall hyetograph.

It should be noted that the CN method requires establishment of empirical relationships between rainfall depth and runoff, which take into account the ground and rainfall characteristics. However, there is a lack of sufficient data to establish such relationships in Hong Kong.

B.4 Unit-Hydrograph Method

This approach assumes that direct runoff is linearly proportional to excess rainfall and the behaviour is time invariant. Details can be found in Chow et al (1988), Bedient & Huber (1992) and Linsley et al (1982). A unit-hydrograph (UH) is the time response of direct surface runoff to a unit effective rainfall occurring uniformly over a watershed at a uniform rate over a specific duration (commonly specified as being 1-hour, 6-hour, or 24 hour). The direct surface runoff is computed by convolution integration:

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} \quad \text{.....} \quad \text{(B.7)}$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

where Q_n = direct runoff at time step n
P_m = excess rainfall at time step m
M = number of time step defining the excess rainfall
Ur = unit hydrograph of the runoff after r (= n-m+1) time steps from the rainfall step

For gauged basins, unit hydrograph can be derived from gauge data. For ungauged basins, synthetic unit hydrographs are often used. Triangular distribution is a common unit hydrograph used. An advantage of using a triangular distribution is that only 3 parameters are needed to characterise a hydrograph: peak runoff, time to reach peak and total duration. Synthetic unit hydrograph formulation based on Clark (1943) and Muskingum routing is commonly used. Still another approach to develop hydrograph shape is based on the IDF, such that the frequency corresponding to any duration agrees with the IDF. The SCS also provided standard shapes of rainfall hyetograph (which is a graphical representation of the distribution of rainfall over time) that can be used to generate runoff hydrograph.

The size of the watershed imposes an upper limit on the applicability of the unit hydrograph method because the center of the rainfall can vary from event to event and each of these events can give a different hydrograph. In the case of a large watershed, the watershed can be divided into smaller sub-basins. Hydrographs can be developed for these sub-basins by the unit hydrograph method and the developed hydrographs can be routed through their respective channels to obtain a composite direct runoff hydrograph.

B.5 Reservoir Routing Method

Routing analysis refers to estimating the variation of runoff hydrograph as water moves through a flow path considering the effects of storage and hydraulic resistance. This method is quoted by DSD (2000). Hydraulic routing considers the mechanics of water flow, such as diffusive wave equation. Hydrologic routing method is based on the continuity equation that the rate of change in storage within a flow segment is equal to the difference between inflow and outflow rate.

$$I - O = \frac{ds}{dt} \quad \text{.....} \quad \text{(B.8)}$$

where I = inflow rate
O = outflow rate
s = storage

A simple case is reservoir routing which considers a known inflow hydrograph and a known relationship between storage and outflow rate (storage-outflow rating curve). The outflow hydrograph is computed by solving the continuity equation.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

B.6 Statistical Analysis of Gauge Data

When the drainage area is large, many methods, such as the Rational and SCS CN methods, are not valid. If sufficient gauge data are available, statistical recurrence analysis can be performed to estimate the runoff corresponding to a selected frequency of occurrence for design purposes. Many agencies, such as the United States Water Resources Council, recommend the use of Log-Pearson Type III distribution for frequency/recurrence analysis.

B.7 Regression Methods

Many agencies, such as the United States Geologic Survey (USGS), developed regression equations relating runoff to rainfall and representative catchment characteristics, such as size, shape, slope and land use. Some of these relationships were developed based on observed data in individual regions and are intended for local use. Some relationships were computed using data from a wide range of sources and were developed for general use (Sauer et al, 1983).

B.8 Research and Development of Analytic Models

Rainfall-runoff investigation and modelling continue to be active areas of research. It is beyond the scope of this report to provide a comprehensive survey of the research and development (R&D) activities in these subjects. However, this section briefly highlights a few areas of the relevant R&D focuses. There are efforts by various agencies to refine the implementation of the runoff estimation methods described above, including developing guidance on the selection of various parameter values and their bounds.

One R&D focus is on monitoring and modelling subsurface processes, especially in natural terrain. Subsurface water movement is complex and it continues for a long period after the rainfall stops. Improved capability in simulating moisture retention, uptake by plants, evapotranspiration and percolation in the upper and lower root zone will lead to better prediction of interflow and various components of baseflow that contribute to runoff.

Monitoring and modelling hydrologic processes of large catchments are challenging due to significant spatial variability in surficial hydraulic characteristics, subsurface conditions and rainfall patterns. Numerical codes are being developed and refined to include details of various surficial and subsurface processes. One particular R&D area is the integrated hydrologic modelling that simulates simultaneously surface water flow, moisture movement in the unsaturated soils above the groundwater table, and groundwater seepage below the groundwater table as a single water system. It addresses implicitly the interaction of the surface water and groundwater regimes. Simulation of the exchange of water between surface water and groundwater is carried out without the need of making assumption on exchange fluxes.

There are R&D efforts on applying data-driven techniques to quantify rainfall-runoff relationship. These techniques include transfer function noise (TFN) models, artificial neural network (ANN) models, fuzzy rule-based models, and nearest neighbor forecasting

Table of Contents
Table of Contents
Table of Contents
Table of Contents

methods. These techniques are applied to available site-specific data for development of local prediction tools.

Real-time monitoring is becoming more readily available as new techniques are developed. These data can be used to update hydrologic model predictions with reduced errors and rainfall forecasting. Various modelling updating methods for adjusting model states (state correction) or predicting future errors (error prediction) are developed.

B.9 Computer Software for Modelling Precipitation-runoff Process

There are many computer programs available for estimation of runoff, ranging from simple design tools to detailed numerical simulation of the physical behaviours of surficial and subsurface hydrologic processes. A few computer tools representing some of the popular computer codes are described in the following sub-sections.

B.9.1 WinTR-55

The USDA NRCS Technical Release 55 (TR-55) entitled "Urban Hydrology for Urban Watershed" (1986) presents simplified procedures for estimating runoff and peak discharges in small watersheds (smaller than 25 square miles). The procedures have been coded in a windows-based software WinTR-55 (2009 version). The TR-55 model begins with a rainfall amount uniformly imposed on the watershed over a specified time distribution. TR-55 includes four 24-hour regional rainfall time distributions. The rainfall distributions are designed to contain the intensity of any rainfall duration for the frequency of the event chosen. That is, the total rainfall over the most intense period of any length of time within the 24-hour period will approximate the rainfall volume due to the rainfall intensity in the IDF corresponding to the rainfall duration equal to the length of time considered.

Mass rainfall is converted to mass runoff by using the SCS CN method. TR-55 provides a table and a figure showing the runoff depth as a function of rainfall volume and *CN*. Runoff is then transformed into a hydrograph by using unit hydrograph theory and routing procedures that depend on runoff travel time through segments of the watershed. Two major parameters are time of concentration and travel time of flow through the segments. Peak rates of discharge and hydrographs are approximated by using procedures described by NRCS (1997). The computations are made based on software TR-20 (see Section B.9.2).

TR-55 also provides methods to calculate the composite *CN* for watersheds with pervious and impervious areas for the cases of connected and unconnected impervious areas in terms of the *CN* of the pervious areas. When the weighted *CN* value is less than 40, other procedure should be used to determine runoff.

B.9.2 WinTR-20

USDA NRCS Technical Release 20 (TR-20) entitled "Computer Program for Project Formulation Hydrology" (1992) is a major revision of the original release in 1965. It is a computer program for the simulation of runoff occurring from single storm events in small

Table of Contents
Table of Contents
Table of Contents
Table of Contents

watersheds less than 25 square miles in size. The procedures have been coded in a windows-based software WinTR-20 (2009 version). The program develops flood hydrographs over heterogeneous watersheds from runoff and routes the flow through stream channels and reservoirs. Either actual or synthetic cumulative rainfall distributions are allowed. Hydrographs, peak discharges, and peak elevations can be obtained at any cross section along the stream, at the outlet of a sub-watershed or a structure. The method is an enhancement of the Rational Method and modified Rational Method. Hydrograph computation is based on SCS curvilinear hydrograph. The SCS CN method is implemented to estimate runoff volume. Reservoir routing methods described by NRCS (1997) were included. Reach routing is computed using a Modified Attenuation-Kinematic method. It allows hydrograph combination and separation at confluences.

B.9.3 HEC-HMS

The Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers (USCOE) has been releasing hydraulic and hydrologic analysis software that has been regarded by the profession as standard tools. The latest computer code HEC-HMS (HEC Hydrologic Modeling System) with graphical user interface (GUI) is a replacement for the legacy software HEC-1 (Flood Hydrograph Package) which was once widely used for hydrologic analysis. Geospatial extensions have been added to produce the HEC-GeoHMS code for use with the geographical information system (GIS) tools developed by the Environmental Systems Research Institute, Inc. (ESRI).

HEC-HMS has the option to specify historical rainfall, frequency-based synthetic rainfall, or Probable Maximum Precipitation. It can use a distributed runoff model for use with distributed rainfall data, such as radar data. It estimates the runoff (overland flow and interflow) due to the specified rainfall event and baseflow using the input watershed properties (such as topography, roughness, and soil characteristics). It simulates overland flow, storage, and the hydraulics of water flowing into and through channels. It includes various runoff volume models, such as the SCS CN method and Green-Ampt infiltration model. Runoff models implemented include unit hydrograph (user-specified based on gauge data, Snyder formulation, SCS method), Muskingum-Cunge formulation, and kinematic wave equations. It also models water control measures such as diversions and storage elements. Soil moisture is tracked during simulation so that the response to wetting and drying can be evaluated.

B.9.4 Storm Water Management Model

The Storm Water Management Model (SWMM) is a distributed, dynamic rainfall-runoff simulation model developed by the United States Environmental Protection Agency (USEPA). The SWMM's main application is for modelling runoff in small urban areas and routing through conveyance systems either for single flood events or long-term events (USEPA, 2010). An SWMM model requires delineation of the study area into sub-catchments that receive precipitation and generate runoff. Sub-catchments are hydrological units of land whose topography and drainage system elements direct surface runoff to a single discharge point. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage devices, pumps, and regulators.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Each sub-catchment surface is treated as a nonlinear reservoir. Inflow comes from precipitation and any designated upstream sub-catchments. There are several outflows, including infiltration, evaporation, and surface runoff. Surface runoff occurs only when the depth of water in the storage elements exceeds the maximum depression storage. Depth of water over the sub-catchment is continuously updated with time by solving numerically a water balance equation over the sub-catchment. Three infiltration models are provided in SWMM including Horton's equation, Green-Ampt method and CN method. Percolation of the infiltrated water is modelled using a three compartment model of groundwater system that includes an upper zone that receives the infiltration, a lower zone beneath it and a deep aquifer.

B.9.5 Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) is a comprehensive watershed scale distributed hydrologic model developed to simulate management impacts in large and complex watersheds (Neitsch et al, 2011). SWAT originated from the USDA's Simulator for Water Resources in Rural Basins (SWRRB) model in 1985. A SWAT model requires delineation of the river basin into sub-basins that may be contributing to individual tributaries. Sub-basin can be further divided into hydrological response units that are grouped based on land cover, soil, and management combinations.

Similar to SWMM, SWAT uses a threshold based on depression storage to initiate runoff and provides all the models except the Horton's equation. SWAT includes some of the most comprehensive models for calculating evapotranspiration losses. SWAT provides a peak runoff rate based on the Rational Method.

B.9.6 Hydrologic Simulation Program-Fortran

The Hydrologic Simulation Program-Fortran originated from the Stanford Watershed Model (Imhoff, 1980). It is a widely used public domain software for modelling of surface water and groundwater flows. It simulates surface runoff over pervious and impervious land segments and stream routing. The hydrologic processes that are simulated include abstractions (such as surface storage, interception and infiltration prior to runoff), interflow (lateral flow in the unsaturated zone above the groundwater table), infiltration and percolation (downward movement of water in the unsaturated zone or near to the saturated zone), overland flow, evapotranspiration, flow routing, and surface flow diversions. A Windows interface program WinHSPF is available to streamline model construction and processing of model output. Other utility tools, such as WDMUtil, are provided to convert file format to use in HSPF simulation.

B.9.7 HydroCAD

The program HydroCAD (HydroCAD, 2004) is a commercial stormwater modelling software with several hydrologic methods implemented. It includes the Rational Method and the CN method and allows the generation of design rainfall events. The methods in TR-55 and TR-20 are implemented in this code.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

B.9.8 MIKE-SHE

MIKE-SHE delivers a truly integrated modelling of groundwater, surface water, recharge and evapotranspiration, and other aspects of hydrology that requires for a integrated model (DHI, 2011). Typical MIKE-SHE applications include integrated catchment hydrology, conjunctive use of surface water and groundwater, floodplain management, groundwater induced flooding, and groundwater remediation. MIKE-SHE can help investigate individual processes of the hydrological cycle in detail with the tailor-made intergraded hydrological model. However, presently there are substantial obstacles in applying such an approach in Hong Kong as most of the input parameters required (e.g. evaporation rates, infiltration rates, soil layering and properties, bedrock levels and overland Manning coefficients) are not readily available.

B.10 References

Bedient, P.B. & Huber, W.C. (1992). *Hydrology and Floodplain Analysis*. Prentice Hall, 801 p.

Chow, V.T., Maidment, D.R. & Mays, L.W. (1988). *Applied Hydrology*, McGraw Hill Education, 537 p.

Clark, C.O. (1943). Storage and the Unit Hydrograph. *Proceedings American Society Civil Engineers. vol. 9*, pp 1333-1360.

DHI (2011). *MIKE SHE User Manual – volume 1: User Guide*. DHI, 332 p.

DSD (2000). *Stormwater Drainage Manual - Planning, Design and Management*. Drainage Services Department, Hong Kong, 130 p.

HydroCAD (2004). *HydroCAD-7 Owner's Manual*. HydroCAd Software Solutions LLC, 160 p.

Imhoff, J.C. (1980). *Users Manual for Hydrological Simulation Program – FORTRAN (HSPF)*. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 678 p.

Izzard, C.F. (1946). Hydraulics if runoff from developed surfaces. *Proceeding, 26th Annual Meeting, Highway Research Board*, Volume 26.

Kirpich, Z.P. (1940). Time of concentration of small watersheds. *Journal of Civil Engineering*, 10(6), ASCE, New York, US, pp 362.

Linsley, R.K., Kohler, M.A. & Paulhus, J.L.H. (1982). *Hydrology For Engineers*. McGraw Hill Education, 508 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Mulvaney, T.J. (1851). On the use of self-registering rain and flood gauges in making observations of the relations of rain fall and of flood discharges in a given catchment. *Proceedings of the Institution of Civil Engineers of Ireland*, 4, pp 18–33.

Neitsch, S.L., Arnold, J.R., Kiniry, J.R. & Williams, J.R. (2011). *Soil and Water Assessment Tool Theoretical Documentation Version 2009, Texas Water Resources Institute Technical Report No. 406*. Texas A&M University System College Station, Texas, 647 p.

NRCS (1997). *National Engineering Handbook, Part 630 "Hydrology"*. United States Department of Agriculture, Natural Resources Conservation Service, 766 p.

Sauer, Vernon B., Thomas, W.O., Jr. Stricker, V.A. & Wilson, K.V. (1983). *Flood Characteristics of Urban Watersheds in the United States*. USGS Numbered Series, 69 p.

Soil Conservation Service (1964). *National Engineering Handbook, Section 4, Hydrology*. Department of Agriculture, Washington, 450 p.

Soil Conservation Service (1972). *National Engineering Handbook, Section 4, Hydrology*. Department of Agriculture, Washington, 762 p.

USDA (1986). *Urban Hydrology for Urban Watersheds (Technical Release 55)*. United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 115 p.

USDA (1992). *Computer Program for Project Formulation Hydrology (Technical Release 20)*. United States Department of Agriculture, Soil Conservation Service, 330 p.

USDA (2009). *Small Watershed Hydrology, WinTR-55 User Guide*. United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 142 p.

USEPA (2010). *Storm Water Management Model, User's Manual, Version 5.0*. United States Environmental Protection Agency, 295 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Appendix C

Design Practice in Other Places

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

List of Tables

Table of Contents
Table of Contents
Table of Contents

C.1 Introduction

This appendix provides an overview of the practice of drainage design in United States (US), United Kingdom (UK), Canada, Australia, France, China, and Taiwan. Most of the commonly used runoff estimation methods described in Appendix B are developed in these places or further refined for implementation there. In some places, there are multiple levels of individual government agencies that deal with drainage and hydrologic analysis issues. Some agencies published guidance documents in the form of hydrology manuals or drainage manuals. Highlights of the major methods used in the selected places are discussed in Section 2.2 of the main text. In general, the Rational Method is most commonly used due to its simplicity. However, due to the limited validity of its major assumptions, some agencies set constraints on situations when it can be used. The curve number method (CN method) has been widely used, especially in the US. It considers major rainfall-infiltration-runoff processes while its data needed are similar to the Rational Method. Hydrograph methods are popular, especially when storage elements are involved. They are often used in designing storage elements and routing analysis. These methods are well accepted in design partly because many computer programs are available.

C.2 United States

C.2.1 Overview

In the US, many federal, state, county and city agencies have developed methods or guidelines for drainage and hydrologic analysis. The surface runoff estimation method selected for a project typically depends on the size of the project, budget and schedule situations, the socioeconomic and safety consequences, ownership of drainage system, maintenance considerations, ease of use of the method, extent of data and information available, preference of the engineer, local practice and government agencies involved. Although there are many layers of agencies concerning with surface runoff issues and they have their own practices, their general approaches and frameworks for different tiers of estimation methods are similar. However, the implications of these methods might be different to account for local situations and individual agencies' practices.

The Rational Method is most commonly used because of its simplicity, despite the frequently raised concerns about its limitations. However, it is generally accepted for use in small catchments. For larger catchments, the Rational Method is also used in preliminary design and the adequacy of the design is confirmed using more sophisticated methods or computer software. The CN method has been widely used in the US for about 50 years. It alleviates some limitations of the Rational Method with a more refined account of subsurface infiltration and only requires basic data similar to that used in the Rational Method. The CN method is implemented in many commonly used hydrologic models, such as TR-20, TR-50, SWMM and HEC-HMS. Hydrograph methods, either based on synthetic hydrographs or hydrographs derived from flow gauge recordings, are commonly used to establish temporal runoff profiles. The resulting flow volume estimation is used for drainage design.

Different agencies have their own criteria for accepting the use of the Rational Method and methods developed by the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA), which include the size of the area, land use, and basin

characteristics. For larger areas, the use of the Rational Method and SCS method is limited. The United States Geological Survey (USGS) has developed empirically-based generic regional and small area regression equations for estimation of runoff in urbanised and undeveloped areas. Some regional agencies developed their only empirical formulas specifically for their service areas. When extensive gauge data are available, statistical techniques to evaluate recurrence characteristics can be used to estimate runoff.

For complex drainage systems, numerical tools are used to estimate design parameters or to confirm the adequacy of the drainage design. Both lumped flow routing and distributed flow routing numerical tools are available. Other sophisticated tools, such as the Hydrologic Simulation Program-Fortran (HSPF) and the Storm Water Management Model (SWMM) codes, have been adopted in some regions for an integrated management of their storm water best management practices (BMP) and low-impact development (LID).

Brief discussions of the above methods, such as the Rational Method, CN method and SCS methods, are included in Appendix B. Some of the computer based models, such as TR-20, TR-50, SWMM, HEC-HMS, and HSPF are also discussed in Appendix B.

C.2.2 Federal Level

At the federal level, the United States Department of Agriculture (USDA) is concerned with natural resources conservation and has been playing a significant role in regard to developing infiltration and runoff estimation methodologies. Their Soil Conservation Service (SCS), currently the Natural Resources Conservation Service (NRCS), developed the curve number method, which has been widely used for over 60 years. The SCS published a revised Technical Release TR-20 in 1998 entitled “Computer Program for Project Formulation Hydrology” for simulating runoff occurring from single storm event in small watersheds less than 25 square miles. It includes the CN method and reach routing. A window-based software WinTR-20 was released to enhance the graphical user interface (GUI) for the TR-20 program. The NRCS published simplified procedures in Technical Release 55 (TR-55) entitled “Urban Hydrology for Urban Watershed” (USDA, 1986). The procedures have been coded in a Windows-based software WinTR-55. These programs have been widely used in the US for design.

The United States Army Corps of Engineers (USACE) of the Department of Defense (DOD) is concerned with projects with waterways, including rivers, streams, channels, and creeks. Their Hydrologic Engineering Center (HEC) produces suites of computer software for hydrologic and hydraulic analysis for public use. The HEC Hydrologic Modeling System (HEC-HMS) is a popular program used in the profession. It includes simulations of overland flows, storages, and flow hydraulics. The CN method and hydrograph runoff model are included. The USACE published engineer manual EM1110-2-1417 (USACE, 1994) entitled “Flood-Runoff Analysis”, which includes the Rational Method, CN method, hydrograph method, and regression method for both gauged and un-gauged basins.

The Federal Highway Administration (FHWA) of the United States Department of Transportation (USDOT) is concerned with projects involving or impacting federal highways. They published a Hydraulic Engineering Circular No. 22 entitled “Urban Drainage Design Manual”, which provides a comprehensive and practical guide for the design of storm

Table of Contents
Table of Contents
Table of Contents
Table of Contents

drainage systems. The peak flow estimation methods provided in the manual include frequency analysis, the Rational Method, USGS regression equations, and the CN method. The methods for developing design hydrographs include unit hydrograph methods using Snyder synthetic unit hydrograph and SCS hydrographs as well as the USGS nationwide urban hydrograph.

The United States Geological Survey (USGS) has developed and compiled nationwide regional regression rural equations and urban equations for use to estimate peak runoff. These equations are included in a computer program called the National Flood Frequency program (NFF). NFF allows quick and easy estimation of peak flows throughout the United States. The USGS also developed a national urban hydrograph method that approximates the shape and characteristics of hydrographs. Dimensionless hydrographs were provided. The design hydrograph is obtained by scaling the dimensionless hydrograph based on time lag and peak flow.

C.2.3 State Level

At the State level, the American Association of State Highway and Transportation Officials (AASHTO) has published Highway Drainage Guidelines and a Model Drainage Manual (MDM), which compiles generic design policies and state-of-the practice design procedures to provide a foundation on which any Federal, State, or local agency can produce its own customised drainage policy and procedure manual. The Departments of Transportation in many States have their own guidance documents. In addition, many States have their Departments of Water Resources (DWR) that also are involved in flood and drainage matters.

Guidelines from different States were reviewed in this study, including “Highway Design Manual” (California Department of Transportation, 2009), “Hydrology” (Connecticut Department of Transportation, 2000), “Drainage Manual” (Florida Department of Transportation, 2010), “Highway Drainage Manual” (Maryland Department of Transportation, 1981), “Drainage Manual” (Michigan Department of Transportation, 2006), “Drainage Manual” (Minnesota Department of Transportation, 2000), “Drainage Manual” (Nevada Department of Transportation, 2006), “Manual on Drainage Design for Highways” (New Hampshire Department of Transportation, 1998), “Drainage Design Manual” (New Jersey Department of Transportation, 2004), “Drainage Design Manual: Volume 1 Hydrology” (New Mexico Department of Transportation, 1995), “Ohio Drainage Manual” (Ohio Department of Transportation, 2009), and “Highway Runoff Manual” (Washington Department of Transportation, 2010). It revealed that most States allow the use of the Rational Method but set limits on its application and may allow the use of alternative methods. Guidelines and limits are set on drainage area, time of concentration, flow length used to derive the time of concentration, equations used to calculate time of concentration, runoff coefficient, minimum rainfall duration and shape of unit hydrograph used. The following tables show some of these limits and guidelines adopted in some States. (The State of Washington does not allow the use of the Rational Method and instead allows the use of the HSPF method for Western Washington and the CN and unit hydrograph methods for Eastern Washington).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table C1 Maximum Drainage Area Allowed for the Rational Method

State	Maximum Drainage Area Allowed	
Arizona	160 acres	0.65 km^2
Connecticut	200 acres	0.81 km^2
Florida	600 acres	2.43 km^2
Iowa	160 acres	0.65 km^2
Maryland	400 acres	1.62 km^2
Michigan	20 acres	0.08 km^2
Minnesota	200 acres	0.81 km^2
Nevada	200 acres	0.81 km^2
New Hampshire	200 acres	0.81 km^2
New Jersey	20 acres	0.08 km^2
New Mexico	5 square miles for rural areas, 150 acres for urban areas	12.9 km^2 for rural areas, 0.61 km^2 for urban areas

Table C2 Alternative Method Used when Drainage Area that is Greater Than the "Maximum Drainage Area Allowed"

State	Method Used when Drainage Area Greater Than Maximum
Arizona	HEC software
Connecticut	USGS regression equations for area greater than 1 square mile
Florida	Frequency analysis USGS regional or local regression equation
Minnesota	Regression and frequency analysis
Nevada	Regression
New Mexico	Unit hydrograph method; USGS regression equations; Frequency analysis

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table C3 Maximum Time of Concentration/Flow Length Allowed

State	Time of Concentration Calculation Method	Maximum Time of Concentration/ Flow Length Allowed
Arizona	Papadakis and Kazan's equation	60 minutes
Connecticut	Hydraulic flow equations	-
Florida	Hydraulic flow equation and Kirpich equation	15 minutes
Iowa	Hydraulic flow equations	-
Maryland	Hydraulic flow equations	400 ft maximum for unpaved areas
Michigan	Hydraulic flow equations	10 hours
Minnesota	Kinematic wave equation and Hydraulic flow equations	0.1 hour to 10 hours; 300 ft of overland flow
Nevada	-	300 ft for flat terrain and 100 ft for steep terrain
New Hampshire	-	Minimum of 10 min
New Jersey	Hydraulic flow equations	10 min to 100 ft over land flow

Table C4 Range of Runoff Coefficient Values

State	Range of Runoff Coefficient Values
Arizona	0.2 to 0.96
Connecticut	0.04 to 0.95
Florida	0.1 to 0.95
Iowa	0.04 to 0.95
Maryland	0.03 to 0.97
Michigan	0.1 to 0.9
Minnesota	0.1 to 0.95
New Hampshire	0.05 to 0.95
New Jersey	0 to 0.99
New Mexico	0.2 to 0.96

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table C5 Design Return Period

State	Design Return Period
Connecticut	10 years for curb drainage (use 25, 50 or 100 years where more important facilities than usual could be affected by flooding); 100 years for culverts in watershed with area greater than 1 square mile
Florida	2 years for temporary roadside ditch (use 25, 50 or 100 years where more important facilities than usual could be affected by flooding); 25 years for drainage canals (use 50 or 100 years where more important facilities than usual could be affected by flooding)
Minnesota	2 to 50 years
Nevada	10 years for urban collectors to 50 years for interstate highways
New Hampshire	10 years for storm sewers to 50 years for interstate culverts
New Jersey	10 years to 100 years
New Mexico	10 years to 100 years

Table C6 Runoff Increase for a Longer Return Period as Suggested in Table C5

State	Runoff Increase Over the Amount for the Usual Case
Connecticut	10% for 25-year recurrence; 20% for 50-year recurrence; 25% for 100-year recurrence
Florida	10% for 25-year recurrence; 20% for 50-year recurrence; 25% for 100-year recurrence

Table of Contents
Table of Contents
Table of Contents
Table of Contents

C.2.4 County and City Levels

In some States, individual counties or equivalent manage their drainage network as an integral system. Some large metropolitan cities also have authorities on local drainage issues. Local water agencies and surveyors deal with water supply involving surface water and groundwater resources. Recent focus on conjunctive water use have driven attention on capturing surface runoff and stream flow for storage and recharging groundwater basins in order to reduce flood hazards and to mitigate drought impacts. Some of these local governments and agencies have their individual hydrologic analysis practices.

C.3 United Kingdom

The Environmental Agency (EA) of the United Kingdom published a technical report on preliminary rainfall runoff management for developments as a guide for regulators, developers, and local authorities. It sets out the key runoff estimation techniques. Three types of runoff models that are universally used in the UK are presented: (1) simple fixed percentage runoff models (such as the Rational Method for catchment area up to 150 ha.), (2) statistical percentage runoff models (such as the Wallingford Procedure for urban applications), and (3) statistical peak flow estimation models (such as the ADAS 345 formula). The modified Rational Method and the Wallingford Procedure are the two key techniques for assessing urban runoff. The Wallingford Procedure is typically the preferred technique. The process is implemented in several modelling software.

Two Wallingford Procedure (WP) urban runoff models, the fixed UK runoff model and the variable UK runoff model, are widely used across the UK and they are both referred to as WP runoff models. Detailed information about these models can be found in the CIRIA report “Drainage for development sites – a guide” (May et al, 2004). The variable UK runoff model is a replacement to the fixed UK runoff model. It expresses the percentage runoff as a function of an effective impervious area factor, moisture depth parameter and 30-day antecedent precipitation index which addresses the lower losses towards the end of long-duration storm event. The effective impervious area factor depends upon the surface condition.

The EA technical report describes three main international drainage packages, Micro-drainage, InforWorks and MOUSE, for drainage networks evaluation. For protection against flooding from drainage system, the CIRIA SUDS manual suggests a design return period of 10-30 years. For protection against flooding from overland flows, a design return period of 100-200 years is suggested.

C.4 Australia

The main guidance for runoff estimation in Australia comes from Australian Rainfall and Runoff (ARR) (Pilgrim, 1998). The unit hydrograph method and the Rational Method are popular. It is a common practice to utilise the Rational Method to obtain a peak flow using rainfall intensity-duration-frequency model. Computer-based runoff routing software, such as RAFTS, RORB, WBNM and URBS are frequently used. RORB is more frequently used for rural sparsely developed catchments, while the others have been widely used for both

Table of Contents
Table of Contents
Table of Contents
Table of Contents

rural and urban catchments. These models involve delineating sub-catchments based on area, slope, and percentage imperviousness. Flow is routed through the sub-catchments resulting in flow hydrographs. ARR established the use of Urban Rational Method (URM) in 1987. It expressed the runoff coefficient as a linear function of impervious fraction for 10-year 1-hr rainfall intensities of 25 mm/hr and 70 mm/hr. The runoff coefficient for other rainfall intensities should be interpolated. The time of concentration calculation is based on the kinematic wave formula.

Queensland published the "Queensland Urban Drainage Manual" (QUDM) (Queensland Department Resources and Mines, 2007). Although it is developed specifically for Queensland, it is used in other States in practice. Instead of using design rainfall based on IDF, modelling of the Probable Maximum Flood (PMF) event is also used, primarily as an allowance for intense rainfall tropical cyclones. The QUDM states that the Rational Method is not suitable for urban catchments greater than 500 ha, and catchments with a time of concentration greater than 30 minutes. It provides tables showing the runoff coefficient values for the 10-year return period as functions of rainfall intensity and impervious fraction. A frequency factor is applied to adjust the runoff coefficients for other design storm events. The frequency adjustment factor ranges from 0.8 for the 1-yr return period to 1.2 for the 100-yr return period. However, the adjusted runoff coefficients should be limited to a maximum value of 1.0 for urban areas. The time of concentration is calculated using velocity method and is limited to a minimum of 5 minutes. The recommended maximum overland sheet flow length ranges from 20 m for steep grassland to 200 m for flat bushland. It is recommended to use Friend's equation (Queensland Department Resources and Mines, 2007) instead of the kinematic wave equation to calculate the overland flow time. For rural catchments, the Bransby-Williams equation, modified Friend's equation (for catchment less than 25 km square), and stream velocity method were recommended. QUDM recommended the use of a 50-year design return period for major system design for drainage paths where there is expected to be good control of surface roughness. A 100-year design return period should be used in situation that it is difficult to predict actual flow conditions. For minor system design, the recommended design return period ranges from 1 year for open space to 10 years for high density urban residential area, except that a 50-year return period should be used for major road cross drainage. The QUDM discusses the use of Clarke-Johnstone Synthetic Unit Hydrograph procedure which involves time-area characteristics and routing through linear storage.

C.5 France

The Rational Method and the hydrograph approach are the most common methods. The publication La ville et son assainissement (Ministry of Public Works, 2003) describes the common methods. The design return period is 10 years for drainage in rural areas, 20 years for residential zones, 30 years for city centers, and 50 years for roadway tunnels. The IDF curves are based on the Montana formula:

$$h = at^{1-b} \quad \text{.....} \quad \text{(C.1)}$$

where h = height (in mm) corresponding to time step t
t = time (in minutes)
a, b = Montana Coefficients

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The coefficients *a* and *b* are supplied by the French Meteorological Office. The Rational Method can be extended to the time-area method. The runoff coefficient values range from 0.2 for residential areas to 0.9 for highly populated areas. Inlet time varies between 5 to 15 minutes. Equations are provided for calculating the inlet time based on length of the catchment, slope, and rainfall intensity. Travel time in the drainage elements are calculated from flow velocity and flow length.

C.6 Taiwan

According to the Soil and Water Conversation Handbook published by Soil and Water Conservation Bureau (2005), the Rational Method is a commonly used method. However, more accurate methods should be used for important projects. The Rational Method can be used for drainage area less than 10 km^2. A table is provided expressing the runoff coefficient as a function of land type for undeveloped, developing and developed areas. Empirical relations are provided for calculating the rainfall intensity as a function of the return period and rain duration. The parameters for various areas in Taiwan were tabulated. Inlet time is calculated based on a travel velocity between 0.3 and 0.6 m/s. The travel time in the drainage system can be calculated using either the Rziha equation, Kraven formula or California formula.

C.7 China

There are four documents relevant to the subject of surface runoff estimation: (1) Code for Design of Outdoor Drainage (GB50014-2006) (The Ministry of Construction of the PRC, 2006), (2) Standard for Flood Control (GB20201-1994) (The Ministry of Water Resources of the PRC, 1994), (3) Code for Design of Flood Control Engineering (CJJ50-1992) (China Northeast Municipal Engineering Design and Research Institute, 1993), and (4) Specification of Design and Construction for Landslide Stabilization (DZ/T-0219-2006). In addition, two volumes of the popular manual "Water Supply and Drainage Design Handbook" provide additional details on the applications of various methods in practice: Volume 6, Outdoor Drainage and Industrial Wastewater Treatment (Beijing General Municipal Engineering Design & Research Institute, 2002) and Volume 7, Flood Control (China Northeast Municipal Engineering Design and Research Institute, 2000) which deal with drainage and flood related hazards, including debris flow and flash flood issues.

Code for Design of Outdoor Drainage (GB50014-2006) (The Ministry of Construction of the PRC, 2006) specifies the Rational Method for estimating runoff rate. Runoff coefficient values range from 0.1 for parks to 0.95 for concrete pavements. Composite runoff coefficient values for urban area are also provided. They vary from 0.2 for low-density development to 0.85 for high-density development. IDF equation is as follows:

$$q = \frac{167 A_1 (1 + C \log P)}{(t + b)^n} \quad \text{.....} \quad \text{(C.2)}$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

where q = design rainfall intensity [L/(s•ha)]
t = duration of rainfall (in minutes)
P = design return period (a)*
A_1, C, n, b = design parameters

*Note: "a" is a unit to quantify the design return period, refer to Appendix A of Code for Design of Outdoor Drainage (GB50014-2006).

The inlet time is generally between 5 to 15 minutes. A multiplier is applied to the travel time in the drainage elements. The multiplier ranges from 1.2 for open channels to 2 for pipes.

In Volume 6, Outdoor Drainage and Industrial Wastewater Treatment (Beijing General Municipal Engineering Design & Research Institute, 2002), the rational formula and IDF equations are provided. The frequency of design storm event depends on factors such as land use, catchment area, slope and average annual-peak daily rainfall. It ranges from 0.33 year to 3 years. The duration of design storm event equals to the sum of the time of initiation and the time of travel in the drainage system. The document points out that the design duration is normally not calculated and 5 to 15 minutes are commonly used. If it needs to be calculated, the velocity method is described. Runoff coefficient ranges from 0.15 for grassland to 0.9 for concrete and asphalt pavements. In selecting a runoff coefficient, the engineer should consider the saturation condition in the soil prior to the design rain event.

Code for Design of Flood Control Engineering (CJJ50-1992) (China Northeast Municipal Engineering Design and Research Institute, 1993) specifies that for urban flood control in areas with more than 30 years of flow data, use frequency analysis of the flow data to estimate runoff and flood level. In areas with more than 30 years of rainfall data and rainfall-runoff relation information, frequency analysis of the rainfall data would be used to calculate the design rainfall event. Standard for Flood Control (GB20201-1994) (The Ministry of Water Resources of the PRC, 1994) specifies flood protection standard for urban city based on 4 city categories defined according to non-farmer population. The design return period ranges from 20 years for category 4 city to over 200 years for category 1 city. For rural areas, the flood protection standard is specified based on 4 categories defined according to population and farm land area. The design return period ranges from 10 years for category 4 to 100 years for category 1. For highways and other roadways, the design return period ranges from 25 years to 100 years based on the importance of the transportation system.

The Specification of Design and Construction for Landslide Stabilization (The Ministry of Land and Resources of the PRC, 2006) presented the following equation for runoff calculation:

$$Q = \frac{0.278CiA}{t^n} \quad \text{.....} \quad (C.3)$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

where Q = runoff rate (in m^3/s)
C = runoff coefficient (dimensionless)
A = catchment area (in km^2)
t = duration (in hour)
n = rainfall reduction factor
i = design rainfall intensity (in mm/hr)

If watershed information is not available, the following equation should be used for watershed greater than or equal to 3 km^2,

$$Q = CiA^{\frac{2}{3}} \quad \text{(C.4)}$$

and the following equation should be used for watershed smaller than 3 km^2.

$$Q = CiA \quad \text{(C.5)}$$

C.8 Canada

The Canadian practice is similar to the US practice. The Transportation Association of Canada (TAC) published a Drainage Manual, which reflects the Canadian drainage practice. In addition, various provinces have their own provincial standards and some cities, such as Calgary, have their own design manuals. The Rational Method, hydrograph approach, and flood frequency analysis are commonly used for runoff estimation. Provincial peak flood maps are available and often used in practice. The following table shows a summary of some key elements of the runoff calculation implemented by the Provinces of Ontario, Alberta, and British Columbia.

Table C7 Comparison of Drainage Design in Different Provinces of Canada (Sheet 1 of 2)

	Ontario	Alberta	British Columbia
Return Period	5 years for minor local roads; 100 years for major transportation system	10 years for local roads; 100 years for major transportation system	5 years for local roads; 200 years for river and channel control
Duration	1 to 6 hours for small watersheds; 12 to 24 hours for watersheds with storage units	Twice time of concentration for small urban area; 1 hour for urban area less than 50 ha; 12 to 48 hours for urban areas with storage elements; 24 hours for rural area	(* no guidance was given)

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table C7 Comparison of Drainage Design in Different Provinces of Canada (Sheet 2 of 2)

	Ontario	Alberta	British Columbia
Watershed Size for Rational Method	< 100 ha	(* no guidance was given)	< 10 km^2
Runoff Coefficient	0.1 to 0.95	0.1 to 0.95; increases if return period > 25 years	0.3 to 1; increases if return period > 10 years
Time of Concentration t_c	Use the Bransby-Williams equation for cases with runoff coefficient > 0.4; use the Airport formula for cases with runoff coefficient < 0.4	(* no guidance was given)	> 5 min for urban area; > 10 min for residential area; > 15 min for undeveloped area; t_c calculation with Water Manage method the catchment area limited to < 10 km^2 (for BC Rational Formula and < 25 km^2 (for SCS Unit Hydrograph Method), and slope gradient; Kirpich formula; Hathaway formula
CN Method Allowed	Yes	Yes	Yes for watershed < 25 km^2
Hydrograph Method	From gauge data; Hydrological modeling for ungauged watersheds	(* no guidance was given)	(* no guidance was given)
Regional Frequency Analysis (see note below)	25-year index flood for medium and large watersheds; Northern Ontario Hydrology Method for watershed area = 1 to 100 km^2	(* no guidance was given)	(* no guidance was given)

Note: The modified index flood method estimates runoff based on the 25-year return period runoff and applies a frequency conversion factor. The Northern Ontario Hydrology Method was adopted in northern Ontario with the consideration of inland lakes effect.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

C.9 References

AASHTO (2005). *Model Drainage Manual*. American Association of State Highway and Transportation Officials, 1428 p.

Arizona Department of Transportation (1993). *Highway Drainage Design Manual Hydrology*. Arizona Department of Transportation (1993), US, 338 p.

Beijing General Municipal Engineering Design & Research Institute (2002). *Water Supply and Drainage Design Handbook, Volume 6, Outdoor Drainage and Industrial Wastewater Treatment*. China Architecture and Building Press, PRC, 725 p.

California Department of Transportation, (2009). *Highway Design Manual*. California Department of Transportation, US, 749 p.

China Northeast Municipal Engineering Design and Research Institute (1993). *Code for Design of Flood Control Engineering (CJJ50-1992)*. China Northeast Municipal Engineering Design and Research Institute, PRC, 43 p.

China Northeast Municipal Engineering Design and Research Institute (2000). *Water Supply and Drainage Design Handbook, Volume 7, Flood Control*. China Architecture and Building Press, PRC, 769 p.

Connecticut Department of Transportation (2000). *Hydrology*. Connecticut Department of Transportation, US, 700 p.

Environment Agency (2005). *Preliminary Rainfall Runoff Management for Developments*. Environment Agency, UK, 128 p.

Florida Department of Transportation (2010). *Drainage Manual*. Florida Department of Transportation, US, 79 p.

Maryland Department of Transportation (1981). *Highway Drainage Manual*. Maryland Department of Transportation, US, 121 p.

May, R. & Kellagher, R. (2004). *Drainage of Development Sites - A Guide*. HR Wallingford, 29 p.

Michigan Department of Transportation (2006). *Drainage Manual*. Michigan Department of Transportation, US, 845 p.

Ministry of Public Works (2003). *La ville et son assainissement*. Ministry of Public Works, France, 503 p.

Minnesota Department of Transportation (2000). *Drainage Manual*. Minnesota Department of Transportation, US, 298 p.

Nevada Department of Transportation (2006). *Drainage Manual*. Nevada Department of Transportation, Hydraulics Section, US, 84 p.

New Hampshire Department of Transportation (1998). *Manual on Drainage Design for Highways*. New Hampshire Department of Transportation, US, 210 p.

New Jersey Department of Transportation (2004). *Drainage Design Manual*. New Jersey Department of Transportation, US. (www.state.nj.us/transportation/eng/documents/RDM).

New Mexico Department of Transportation (1995). *Drainage Manual: Volume 1 Hydrology*. New Mexico Department of Transportation, US, 157 p.

Ohio Department of Transportation (2009). *Ohio Drainage Manual*. Ohio Department of Transportation, US, 212 p.

Pilgrim, D.H. (1998). *Australian Rainfall and Runoff, A Guide to Flood Estimation, Volume 1*. Institution of Engineers, Australia, 374 p.

Queensland Department Resources and Mines (2007). *Queensland Urban Drainage Manual – Volume 1 Second Edition 2007*. Queensland Department Resources and Mines, Australia, 430 p.

Road and Transportation Association of Canada, (1982). *Drainage Manual Volume 1 and 2*. Road and Transportation Association of Canada, 466 p.

Sinclair Knight Merz (2009). *Australian Rainfall and Runoff Revision Project 7: Baseflow for Catchment Simulation, Stage 1 Report – Volume 1 – Selection of Approach*. Department of Climate Change, Australia, 121 p.

Singh, R.N. & Reed, S.M. (1988). Mathematical modelling for estimation of water inflow. *International Journal of Mine Water*, Vol. 7, No. 3, September 1988, pp 1-34.

Soil and Water Conservation Bureau (2005). *Soil and Water Conversation Handbook*. Soil and Water Conservation Bureau, Taiwan, 692 p.

The Ministry of Construction of the PRC (2006). *Code for Design of Outdoor Drainage (GB50014-2006)*. The Ministry of Construction of the PRC, PRC, 88 p.

The Ministry of Land and Resources of the PRC (2006). *Specification of Design and Construction for Landslide Stabilization*. The Ministry of Land and Resources of the PRC, PRC, 57 p.

The Ministry of Water Resources of the PRC (1994). *Standard for Flood Control (GB20201-1994)*. The Ministry of Water Resources of the PRC, PRC, 29 p.

The University of Western Sydney (2009). *Australian Rainfall and Runoff Revision Project 5: Regional Flood Method, Stage 1 Report*. Department of Climate Change, Australia, 197 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

UNSW Water Research Centre (2010). *Australian Rainfall and Runoff Revision Project 4: Continuous Rainfall Sequences at a Point, Stage 1 Report*. Department of Climate Change, Australia, 100 p.

USACE (1994). *Flood-Runoff Analysis.* Department of the Army, U.S. Army Corps of Engineers, US, 214 p.

USDA (1986). *Urban Hydrology for Urban Watersheds(Technical Release 55)*, United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 115 p.

Washington Department of Transportation (2010). *Highway Runoff Manual.* Washington Department of Transportation, US, 605 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Appendix D

Times of Concentration Estimated for Four WSD Watersheds

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

List of Tables

Table of Contents
Table of Contents
Table of Contents

List of Figures

Table of Contents
Table of Contents
Table of Contents

D.1 WSD Stream Gauge Data

WSD operates a network of stream flow gauges for water resources planning purpose, and has been collecting stream and catchment yield data from 19 gauging stations in Hong Kong. These watersheds have sizes ranging from 0.75 km^2 (at Tsak Yue Wu Upper) to 70 km^2 (at High Island). Data collection commenced in 1945 at 3 gauging stations at Tai Tam Reservoir, Kowloon Reservoir and Aberdeen Reservoir. By 1979, data collection has covered all 19 gauging stations.

At each gauging station, a data logger is connected to the float well system to record water level of the catchwater at an interval of once every 15 minutes. After obtaining the water level records, the flow rates in the catchwater are then determined using a conversion table, which has been established using hydraulic equations with consideration of the catchwater size and weir type. The accuracy of the device for water level measurement is 1 mm.

Regular on-site servicing and maintenance of the data logging system, including inspection of data loggers, changing of batteries and collection of data cards, are carried out once every 3 weeks. During the inspection, the water level in the catchwater is recorded manually outside the gauging station. In the event that the water level measurement is inconsistent with the record collected by data logger, calibration will be carried out on site and adjustments to the data logger record will be made.

D.2 Analysis of Four WSD Watersheds

D.2.1 Characteristics of Watersheds

In this review, stream gauge data collected from 4 WSD watersheds have been selected for analysis of the time of concentration, runoff coefficient and peak runoff. These watersheds are identified as Sham Wat, Tai Lam Chung ‘A’, Tai Lam Chung ‘B’ and Tsak Yue Wu Upper by the WSD. Their locations are shown in Figure D1, and their extents are given in Figures D2 to D5. With detailed aerial photograph interpretations, site characteristics including the surface cover of the watersheds are identified which are given in Table D1.

These four WSD watersheds were selected for analysis in view of their sizes being relatively small (about 1 km^2) which are comparable to the sizes of natural slopes normally encountered in the LPMit Programme. These watersheds are located at various regions with the territory of Hong Kong, providing a good geographical spread of the collected data.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

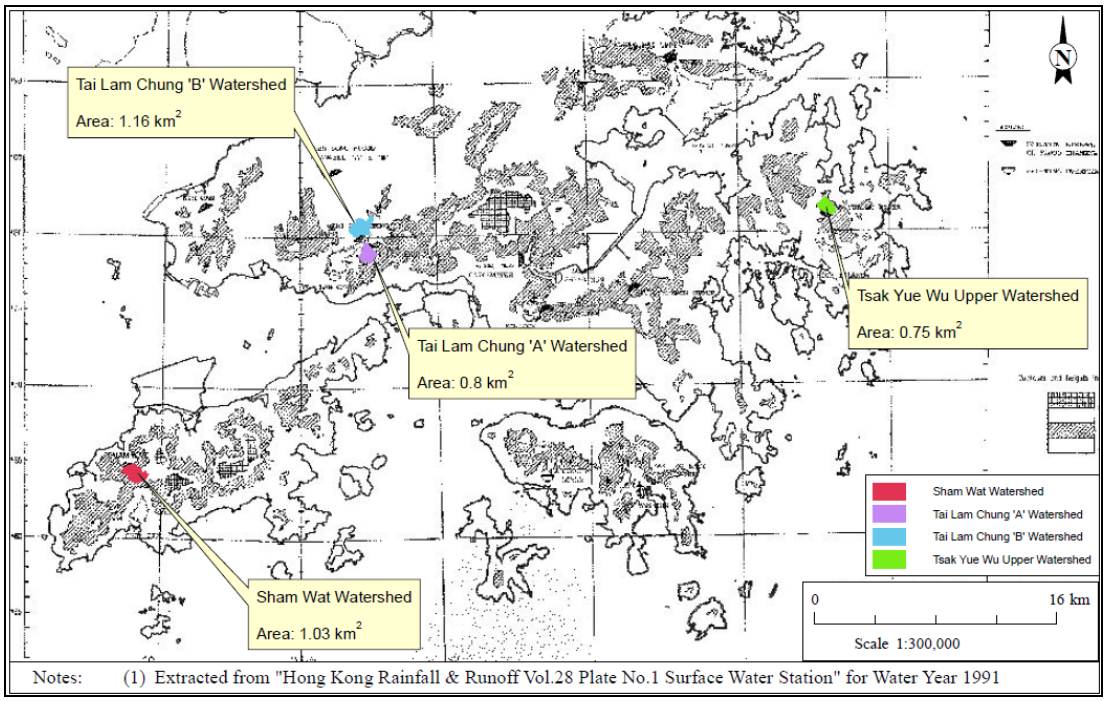


Figure D1 Location of the Four Selected WSD Watersheds

Figure D2 3D Terrain Model for Sham Wat Watershed

Table of Contents
Table of Contents
Table of Contents
Table of Contents

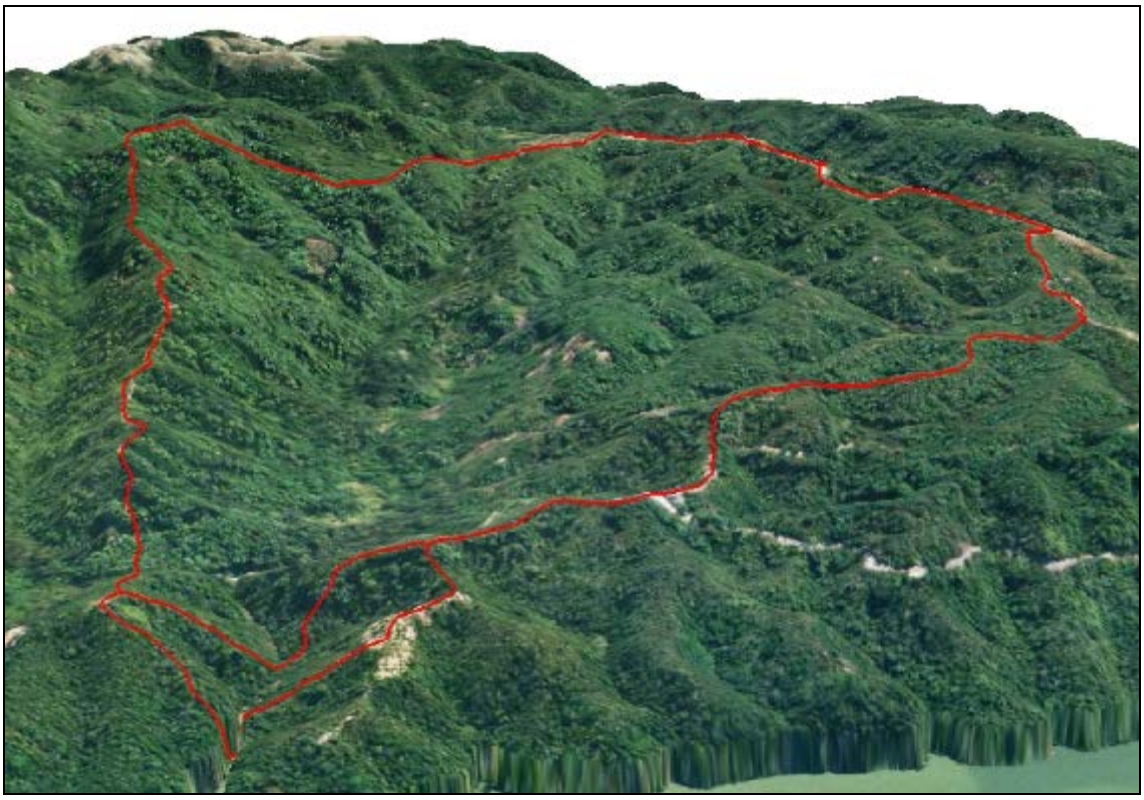


Figure D3 3D Terrain Model for Tai Lam Chung 'A' Watershed

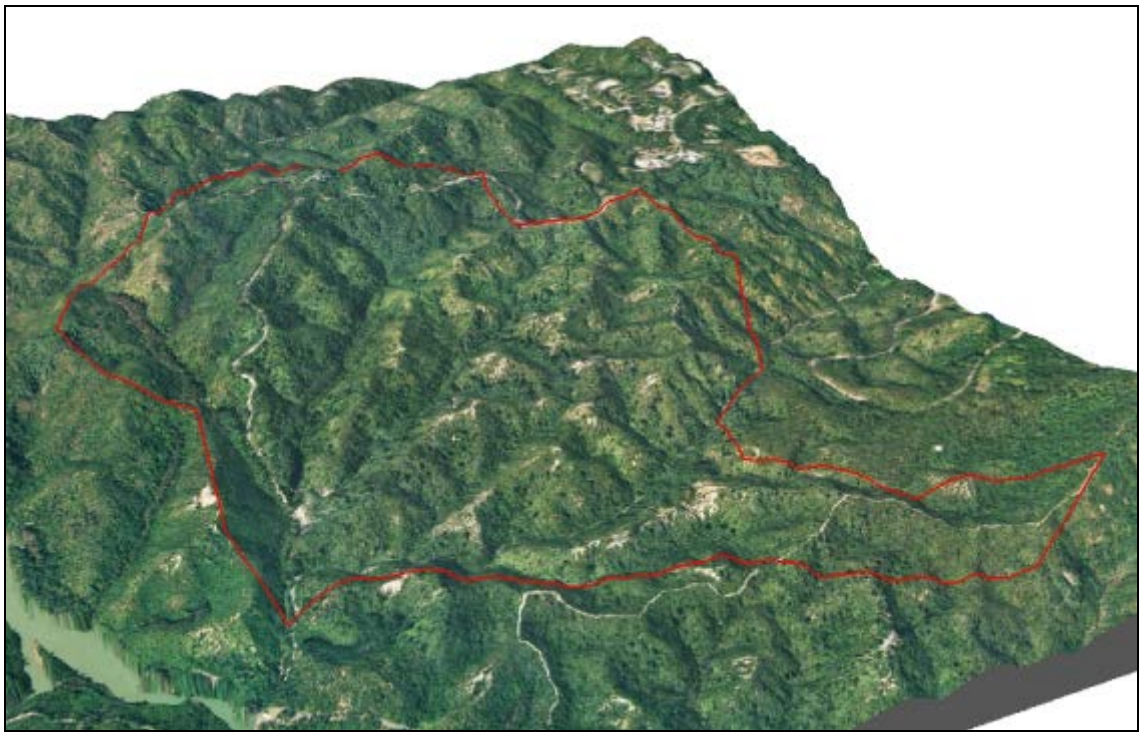


Figure D4 3D Terrain Model for Tai Lam Chung 'B' Watershed

Table of Contents
Table of Contents
Table of Contents
Table of Contents

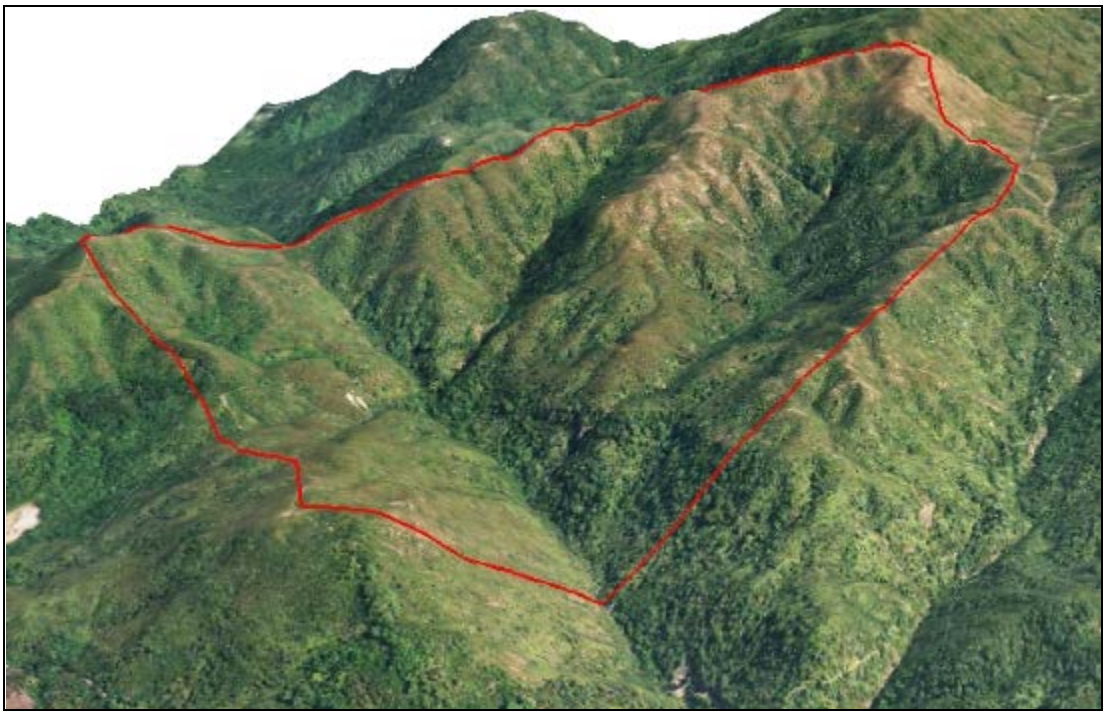


Figure D5 3D Terrain Model for Tsak Yue Wu Upper Watershed

Table D1 Site Characteristics Developed from Detailed Aerial Photograph Interpretation of the Four Selected WSD Watersheds

WSD Watershed	Catchment Size (km^2)	Longest Flow Path (m)	Old Terraces	Grassland	Trees and Shrubs	Rocky Ground	Nearest Raingauge(s)
Sham Wat	1.03	1,735	0%	8%	72%	20%	N17, N19
Tai Lam Chung 'A'	0.80	1,462	6%	0%	73%	21%	N10, N32
Tai Lam Chung 'B'	1.16	1,550	14%	5%	81%	0%	N10, N31
Tsak Yue Wu Upper	0.75	1,300	3%	0%	48%	49%	N13

D.2.2 Time of Concentration

D.2.2.1 Bransby-Williams Equation

Bransby-Williams equation provides an empirical relationship between time of concentration and catchment area, average slope gradient and length of flow path. It can be expressed mathematically as follows:-

Table of Contents Table of Contents Table of Contents Table of Contents

$$t_c = \frac{0.14465L}{H^{0.2}A^{0.1}} \quad \text{.....} \quad \text{(D.1)}$$

where t_c = time of concentration (in min)
A = catchment area (in m^2)
H = average slope (in m per 100 m)
L = length of flow path (in m)

Many practitioners use the whole catchment area to calculate the time of concentration, even if the catchment has been channelled and straightened in places. As pointed out by GEO (1984), this could lead to over-estimation of the time of concentration. GEO (1984) recommends that the time of concentration should be calculated by adding the time of travel within the drainage channel (using hydraulic equations) to the time of concentration calculated for the remote sub-catchment to the drainage channel (using Bransby-Williams equation).

In this review, prominent natural drainage channels are observed at Sham Wat and Tsak Yue Wu Upper.

The time of concentration estimated for the four WSD watersheds using Bransby-Williams equation is given in Table D2 which shows that the time of concentration would be overestimated if the presence of prominent drainage channels is ignored at Sham Wat and Tsak Yue Wu Upper.

Table D2 Time of Concentration Estimation Using Bransby-Williams Equation

Location	t_c (ignoring prominent channels)	t_c (considering prominent channels) (see Note 1)
Sham Wat	33.8 min (over-estimated)	17.9 min
Tai Lam Chung 'A'	33.2 min	33.2 min (see Note 2)
Tai Lam Chung 'B'	33.4 min	33.4 min (see Note 2)
Tsak Yue Wu Upper	26.2 min (over-estimated)	14.3 min

Notes:
(1) Bransby-Williams equation for remote sub-catchments and hydraulic equations for drainage channels within catchment (as recommended in GEO, 1984).
(2) There are no prominent drainage channels in Tai Lam Chung 'A' and Tai Lam Chung 'B'.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

D.2.2.2 Other Empirical Equations

There is not much experience in Hong Kong of using empirical equations other than Bransby-Williams equation to estimate the time of concentration. In this review, attempts have been made to estimate the time of concentration for the four WSD watersheds using other equations commonly adopted worldwide, such as Kirpich equation, Morgali & Linsley equation and Papadakis and Kazan equation.

Kirpich equation can be expressed mathematically as follows:

$$t_c = 0.0078 \frac{L^{0.77}}{S^{0.385}} F_s \quad \text{.....} \quad (D.2)$$

where t_c = time of concentration (in min)
L = length of travel (in ft)
S = slope (in ft/ft)
F_s = 1.0 for natural basins with well-defined channels, overland flow on bare earth, and mowed grass roadside channels
= 2 for overland flow on grassed surfaces
= 0.4 for overland flow on concrete or asphaltic surfaces
= 0.2 for concrete channels

Morgali & Linsley equation can be expressed mathematically as follows:

$$t_c = \frac{0.94(nL)^{0.6}}{i^{0.4} S^{0.3}} \quad \text{.....} \quad (D.3)$$

where t_c = time of concentration (in min)
i = design rainfall intensity (in inch/hr)
n = manning surface roughness (dimensionless)
L = length of flow (in ft)
S = slope of flow (dimensionless)

Papadakis and Kazan equation can be expressed mathematically as follows:-

$$t_c = 11.4 L^{0.5} K_b^{0.52} S^{-0.31} i^{-0.38} \quad \text{.....} \quad (D.4)$$

where t_c = time of concentration (in hr)
L = the length of the longest flow path (in mile)
K_b = the watershed resistance coefficient
S = the slope of the longest flow path (in ft/mile)
i = the average rainfall intensity (in in/hr) for a duration of rainfall equal to t_c , subject to a minimum of 10 minutes

Time of concentration estimated using these empirical equations are given in Table D3.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table D3 Time of Concentration Estimated Using Other Empirical Equations

Location	Kirpich	Morgali and Linsley	Papadakis and Kazan
Sham Wat	14.5 min	17.5 min	14.87 min
Tai Lam Chung 'A'	26.7 min	19.2 min	22.05 min
Tai Lam Chung 'B'	33.8 min	19.5 min	28.84 min
Tsak Yue Wu Upper	18.6 min	14.5 min	12.06 min

D.2.2.3 Hydraulic Flow Equations

Hydraulic flow equations are widely used in the US and other places for estimation of time of concentration. In this method, the time of concentration is given by summing up all the travel times computed using wave equation for sheet flow, shallow concentrated flow and Manning's equations for open channel flow.

Sheet flow travel time can be estimated using the following wave equation.

$$T_{ti} \frac{K_u}{I^{0.4}} \left(\frac{nL}{\sqrt{S}} \right)^{0.6} \quad \text{.....} \quad \text{(D.5)}$$

where T_{ti} = sheet flow travel time (in min)
n = roughness coefficient
L = flow length (in m or ft)
I = rainfall intensity (in mm/hr or in/hr)
S = surface slope (in m/m or ft/ft)
K_u = empirical coefficient equal to 6.92 (0.933 in English units)

Shallow concentrated flow velocity can be estimated using the following Manning's equation.

$$V = K_u k S_p^{0.5} \quad \text{.....} \quad \text{(D.6)}$$

where V = velocity (in m/s or ft/s)
K_u = 1.0 (3.28 in English units)
k = intercept coefficient
S_p = slope (in percent)

Open channel flow velocity can be estimated using the following Manning's equation.

$$V = \frac{K_u}{n} R^{2/3} S^{1/2} \quad \text{.....} \quad \text{(D.7)}$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

where V = velocity (in m/s or ft/s)
K_u = units conversion factor equal to 1 (1.49 in English units)
n = roughness coefficient
R = hydraulic radius
S = slope (in m/m or ft/ft)

The times of concentration estimated for the four WSD watersheds using the hydraulic flow equations are given in Table D4. The first 90 m of the flow path was assumed to be sheet flow at each watershed, followed by shallow concentrated flow. Open channel flow was not adopted in the analysis.

Table D4 Time of Concentration Estimated Using Hydraulic Flow Equations

Location	Sheet Flow (t_1)		Shallow Concentrated flow, Segment 1 (t_2)		Shallow Concentrated flow, Segment 2 (t_3)		Time of Concentration
	Surface property	Time of flow (min)	Surface property	Time of flow (min)	Surface property	Time of flow (min)	$t_c = t_1 + t_2 + t_3$ (min)
Sham Wat	Dense Grasses	3.29	grassed water way	3.99	grassed water way	10.1	17.38
Tai Lam Chung 'A'	Dense Grasses	3.05	grassed water way	8.73	grassed water way	8.5	20.28
Tai Lam Chung 'B'	Dense Grasses	4.72	grassed water way	5.96	grassed water way	19.65	30.33
Tsak Yue Wu Upper	Dense Grasses	5.13	grassed water way	6.86	grassed water way	2.58	14.57

D.2.2.4 Stream Gauge Data Analysis

Attempts have been made in this review to estimate the time of concentration using the WSD gauge data. Two approaches have been adopted; they are the point of inflection

Table of Contents Table of Contents Table of Contents Table of Contents

approach and the uniform rainfall approach. A brief description of these approaches is given in the following paragraphs.

Point of Inflection Approach

Barnes (1939) suggested that the recession limb of a hydrograph (by a single rainfall event) can generally be decomposed into three different exponential terms, where each exponential term represents a different source of water discharged from the watershed. The changing slope in the semi-logarithmic plot is an indication of the decreasing contribution of surface runoff to the discharge. Therefore, by plotting the recession curve in a semi-log plot, there will be a sudden change in slope at the point of inflection since the recession curve and the base flow curve have different slopes. The time of concentration could be estimated as the time from the end of rainfall event to the point of inflection of the recession curve of the hydrograph (Figure D6).

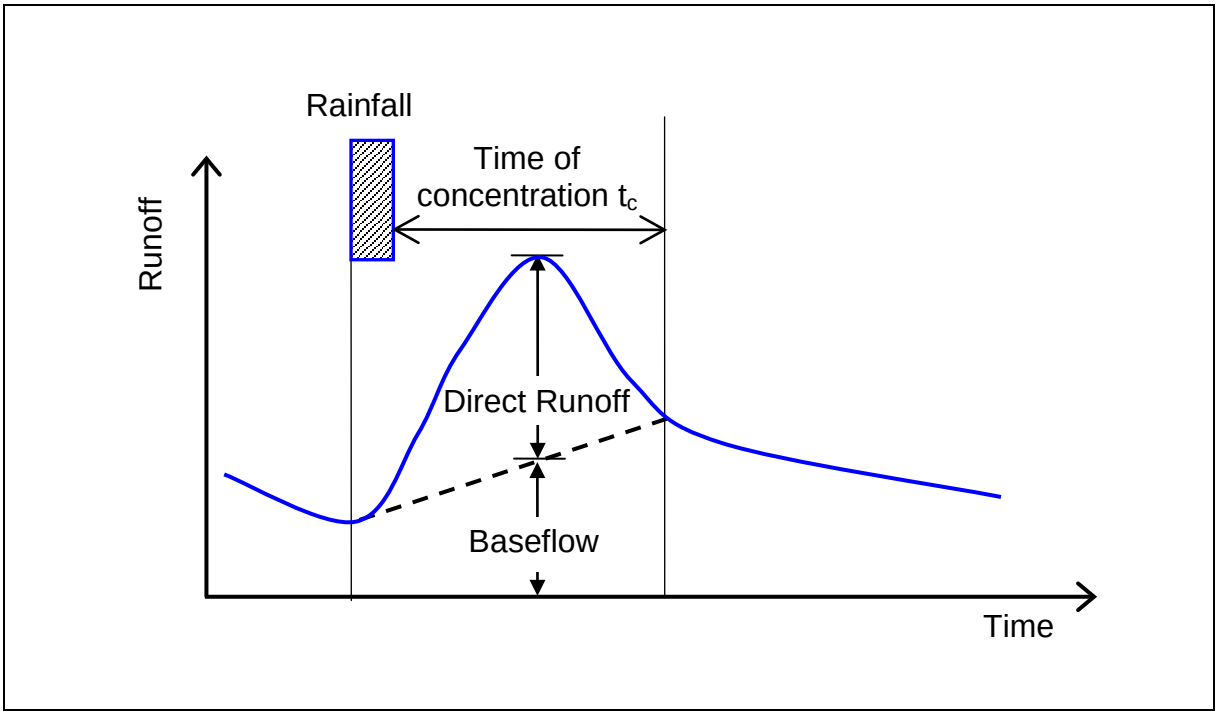


Figure D6 Time of Concentration by Point of Inflection

In this review, 20 single rainfall events (6 at Sham Wat, 4 at Tai Lam Chung 'A', 5 at Tai Lam Chung 'B' and 5 at Tsak Yue Wu Upper) have been selected for the estimation of time of concentration. Figure D7 shows a typical runoff hydrograph arising from a single rainfall event recorded at Sham Wat, on which the time of concentration estimated using the point of inflection approach is indicated. The time of concentration estimated using this approach is found to range from 45 minutes to 1 hour 15 minutes. Results of the estimation for four watersheds are given in Table D5.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

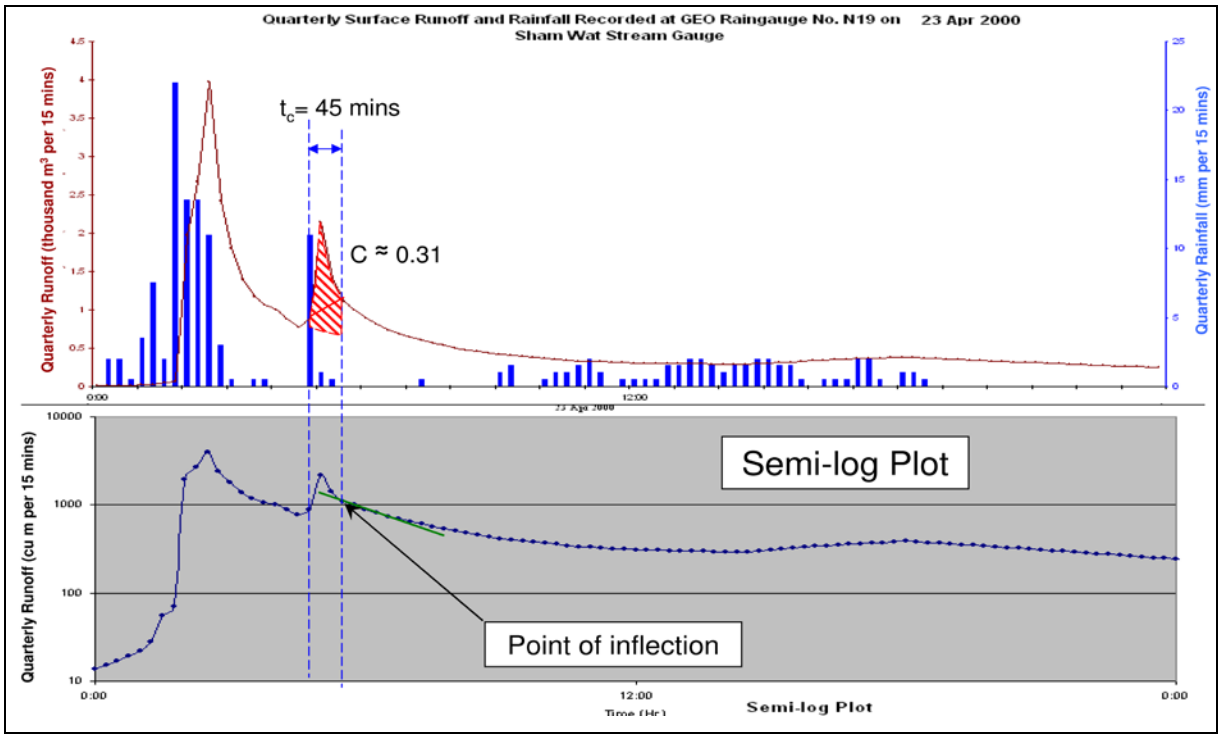


Figure D7 Typical Hydrograph at Sham Wat Watershed, Showing the Estimated Time of Concentration Using the Point of Inflection Approach

Table D5 Summary of the Rainfall Analysis for Four WSD Watersheds Using the Point of Inflection Approach

Sham Wat		Tai Lam Chung 'A'		Tai Lam Chung 'B'		Tsak Yue Wu Upper	
Date	Estimated t_c	Date	Estimated t_c	Date	Estimated t_c	Date	Estimated t_c
23/4 /2000	45 min	11/6 /2001	60 min	13/7 /2001	1hr15min	26/7 /2001	1hr15min
2/8 /2000	1 hr 15 min	20/7 /2005	1 hr 15 min	17/9 /2002	1hr15min	21/9 /2001	60 min
17/9 /2002	60 min	13/8 /2005	1 hr 15 min	9/6 /2006	60 min	15/9 /2002	60 min
10/6 /2003	60 min	9/6 /2006	60 min	20/7 /2005	1hr15min	8/5 /2004	60 min
13/8 /2005	60 min	-	-	16/7 /2006	60 min	9/6 /2006	45 min
3/8 /2006	45 min	-	-	-	-	-	-

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Uniform Rainfall Approach

Figure D8 below shows the typical runoff hydrographs arising from a uniform rainfall event with duration (T) shorter than, equal to, and longer than the time of concentration of a catchment (t_c). As can be seen, when a uniform rainfall occurs longer than the time of concentration (i.e. $T > t_c$), the surface runoff will become steady. As such, the time of concentration could be taken as the time from the beginning of the uniform rainfall to the point where runoff becomes steady.

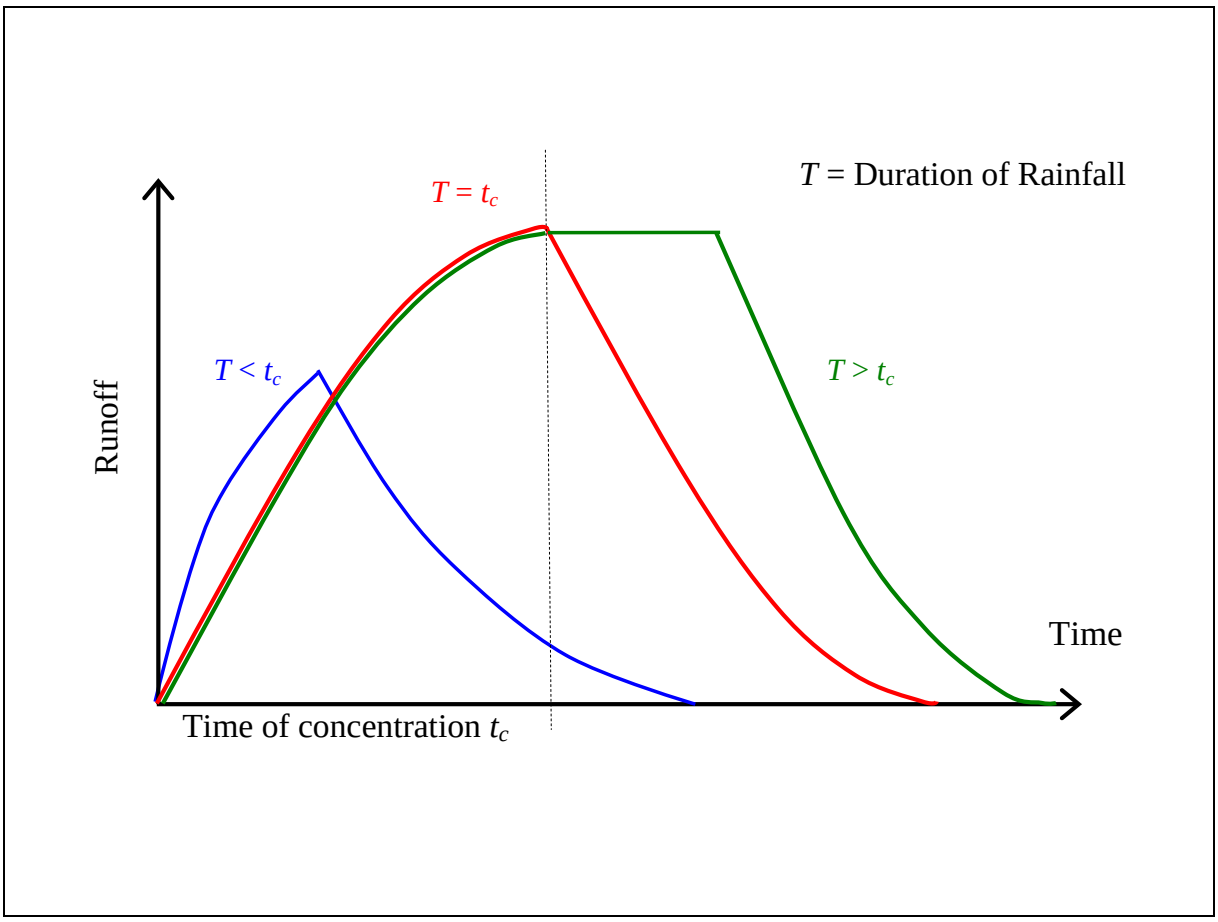


Figure D8 Typical Runoff Hydrographs Arising a Uniform Rainfall

In this review, 25 approximately uniform rainfall events (8 at Sham Wat catchment, 5 at Tai Lam Chung 'A', 8 at Tai Lam Chung 'B' and 4 at Tsak Yue Wu Upper) have been identified for the estimation of time of concentration. Figure D9 shows a typical runoff hydrograph arising from a uniform rainfall event recorded at Sham Wat, on which the time of concentration estimated using the uniform rainfall approach is indicated. The time of concentration estimated using this approach is found to range from 30 minutes to 2 hour 15 minutes. Results of the estimation are given in Table D6.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table D6 Summary of the Rainfall Analysis for Four WSD Watersheds Using the Uniform Rainfall Approach

Sham Wat		Tai Lam Chung 'A'		Tai Lam Chung 'B'		Tsak Yue Wu Upper	
Date	Estimated t_c	Date	Estimated t_c	Date	Estimated t_c	Date	Estimated t_c
15/7 /2001	30-45min	9/8 /2002	1hr - 1hr15min	6/7 /2001	45-60min	19/8 /2005	1hr15min - 1hr30min
5/5 /2003	45-60min	10/6 /2003	45-60min	1/9 /2001	1hr - 1hr15min	13/9 /2006	2hr - 2hr15min
29/8 /2004	45-60min	15/6 /2005	1hr - 1hr15min	20/5 /2002	1hr15min - 1hr30min	6/6 /2008	1hr15min - 1hr30min
15/6 /2005	45-60min	3/5 /2006	1hr - 1hr15min	10/6 /2003	30-45min	8/8 /2008	45min
20/8 /2005	45-60min	25/6 /2008	1hr30min - 1hr45min	15/6 /2005	30-45min	-	-
20/8 /2005	45-60min	-	-	3/5 /2006	45-60min	-	-
7/6 /2008	45-60min	-	-	2/6 /2006	45-60min	-	-
25/6 /2008	45-60min	-	-	25/6 /2008	1hr30min - 1hr45min	-	-

D.2.3 Discussion on Time of Concentration

The estimated time of concentration using various methods is summarized in Table D7. As can be seen in the Table, the time of concentration estimated by most of the empirical equations and hydraulic flow equations give very close results. Taking Sham Wat as an example, the estimated time of concentration is 17.9 minutes by Bransby-Williams equation (with considering prominent channels), 14.5 minutes by Kirpich's equation, 17.5 minutes by Morgali and Linsley equation, 14.9 minutes by Papadakis and Kazan equation, and 17.4 minutes by the hydraulic flow equations.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

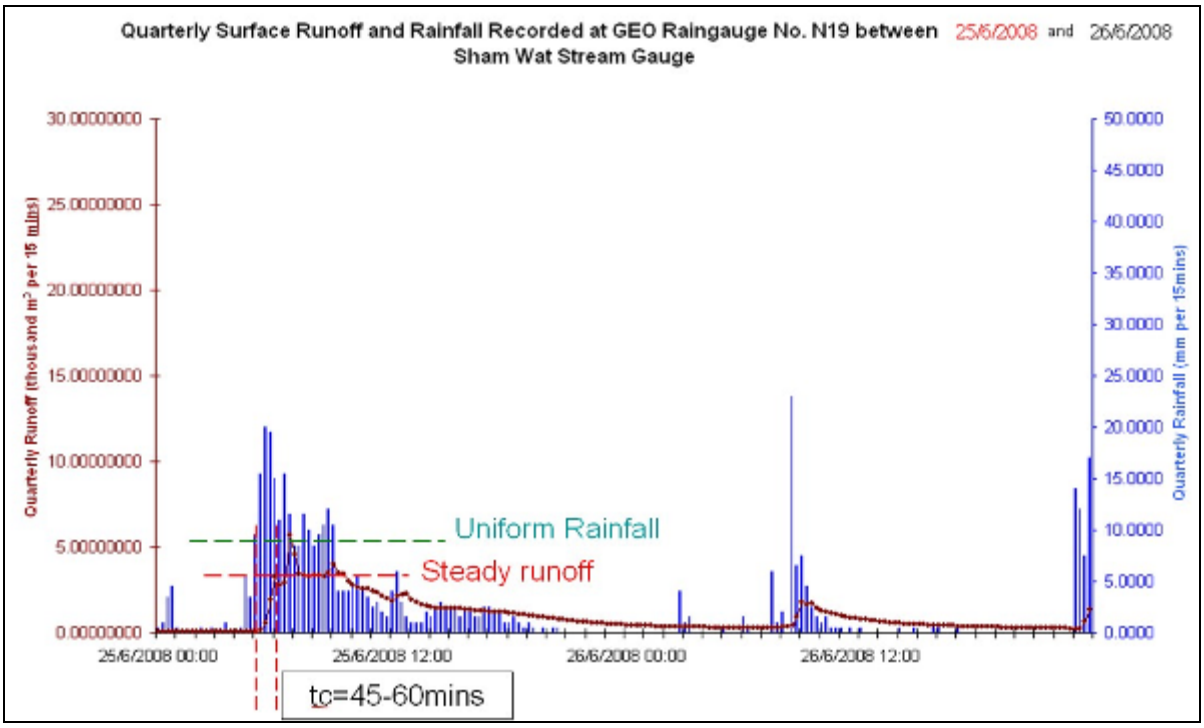


Figure D9 Typical Hydrograph at Sham Wat Watershed, Showing the Estimated Time of Concentration Using the Uniform Rainfall Approach

As shown in Table D7, WSD's stream gauge data consistently give much higher time of concentration than the other methods, irrespective of whether the point of inflection approach or the uniform rainfall approach was used in the estimation.

It is worth noting that the present analysis is restrained by the runoff measurement frequency i.e. at 15-minute intervals. In estimating the time of concentration of the four WSD watersheds (which is within 30 minutes), resolution of 15-minute interval data is unlikely to be refined enough for an accurate estimation.

In the point of inflection approach, a further limitation of the WSD data is that the analysed rainfall (which satisfied the criteria of a single rainfall event occurring in a unit time) is relatively small in magnitude, and the antecedent rainfall was rarely heavy enough to saturate the ground. This setting is likely to give rise to higher initial rainfall absorption thus a "longer" apparent time of concentration. If the ground was fully or almost fully saturated prior to the single rainfall events, the "observed" time of concentration could have been shorter.

In the uniform rainfall approach, the time of concentration was taken as the time from the beginning of the uniform rainfall to the point where runoff becomes steady. This approach is only valid in site settings where there are no (or limited) baseflows due to antecedent rainfalls. In the case of the WSD gauge data where significant baseflows were observed, the uniform rainfall approach is likely to result in "longer" time of concentration.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table D7 Summary of Times of Concentration Estimated by Various Methods

Water-sheds	Time of Concentration							
	Empirical Estimation Equations					Hydraulic Flow Equations	Stream Gauge Data	
	Bransby-Williams		Kirpich	Morgali and Linsley	Papadakis and Kazan		Point of Inflection	Uniform Rainfall
	Ignoring Prominent Channels	Considering Prominent Channels (see Note 1)						
Sham Wat	33.8 min (over-estimated)	17.9 min	14.5 min	17.5 min	14.9 min	17.4 min	45min - 1hr15min	30 - 60 min
Tai Lam Chung 'A'	33.2 min	33.2 min (see Note 2)	26.7 min	19.2 min	22.1 min	20.3 min	60mins - 1 hr 15 min	45 min - 1hr45 min
Tai Lam Chung 'B'	33.4 min	33.4 min (see Note 2)	33.8 min	19.5 min	28.8 min	30.3 min	60mins - 1 hr 15 min	30 min - 1hr45 min
Tsak Yue Wu Upper	26.2 min (over-estimated)	14.3 min	18.6 min	14.5 min	12.1 min	14.6 min	45mins - 1hr15mins	45 min - 2hr15mins

Notes:
(1) Bransby-Williams equation for remote sub-catchments and hydraulic equations for drainage channels within catchment (as recommended in GEO (1984)).
(2) There are no prominent drainage channels in Tai Lam Chung 'A' and Tai Lam Chung 'B'.

It may be concluded that the time of concentration estimated using the point of inflection approach or the uniform rainfall approach is likely to give rise to a "longer" time than those estimated by other methods, which is in line with the observations noted in this review and summarized in Table D7.

D.3 References

Barnes, B.S. (1939). The structure of baseflow recession curves. *Transactions of the American Geophysical Union* 20: pp 721-725.

GEO (1984). *Geotechnical Manual for Slopes (Second Edition)*. Geotechnical Engineering Office, Hong Kong, 302 p. (2011 Reprinted)

Wilson, E.M. (1990). *Engineering Hydrology*. ELBS, UK, 348 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Appendix E

Observed and Design Peak Runoffs at Four WSD Watersheds

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Contents

List of Tables

Table of Contents
Table of Contents
Table of Contents

List of Figures

Table of Contents
Table of Contents
Table of Contents

E.1 Observed and Design Peak Runoff

In this review, a comparison of the peak runoffs observed in the four WSD watersheds has been made with the design peak runoffs estimated using the Rational Method with the assumptions shown in Table E1.

Table E1 Assumptions Used in Estimating Design Peak Runoff

Runoff Coefficient	Scenario A: C = 0.4. Scenario B: C = weighted average coefficient of rocky ground (C = 0.9) and permeable grounds (C = 0.4). Scenario C: C = weighted average coefficient of rocky ground and other grounds plus increase due to antecedent rainfall (C for rocky ground taken as 1.0 and 50% increase in C for permeable ground). The increased value of C is capped at unity. Scenario D: C = 1.0 (theoretical maximum).
Time of Concentration	Estimated using hydraulic equations for drainage channels and Bransby-Williams equation for sub-catchments.
Design Return Period	200 years.
Design Rainfall Intensity	From IDF of GEO TGN 30.

The peak runoffs observed each year at the 4 WSD watersheds and the design peak runoffs calculated for Scenarios A to D are shown in Figures E1 to E4. As can be seen in these figures, the peak runoffs observed at the four WSD watersheds are all enveloped by the design peak runoffs evaluated considering the effect of rocky land and antecedent rainfalls (i.e. Scenario C).

The equivalent drainage channel size to convey different estimations of the design peak runoff is also presented in Figures E1 to E4. A U-channel with a slope gradient 1:100 has been assumed in the size estimation. The drainage size was rounded up to the nearest 100 mm.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

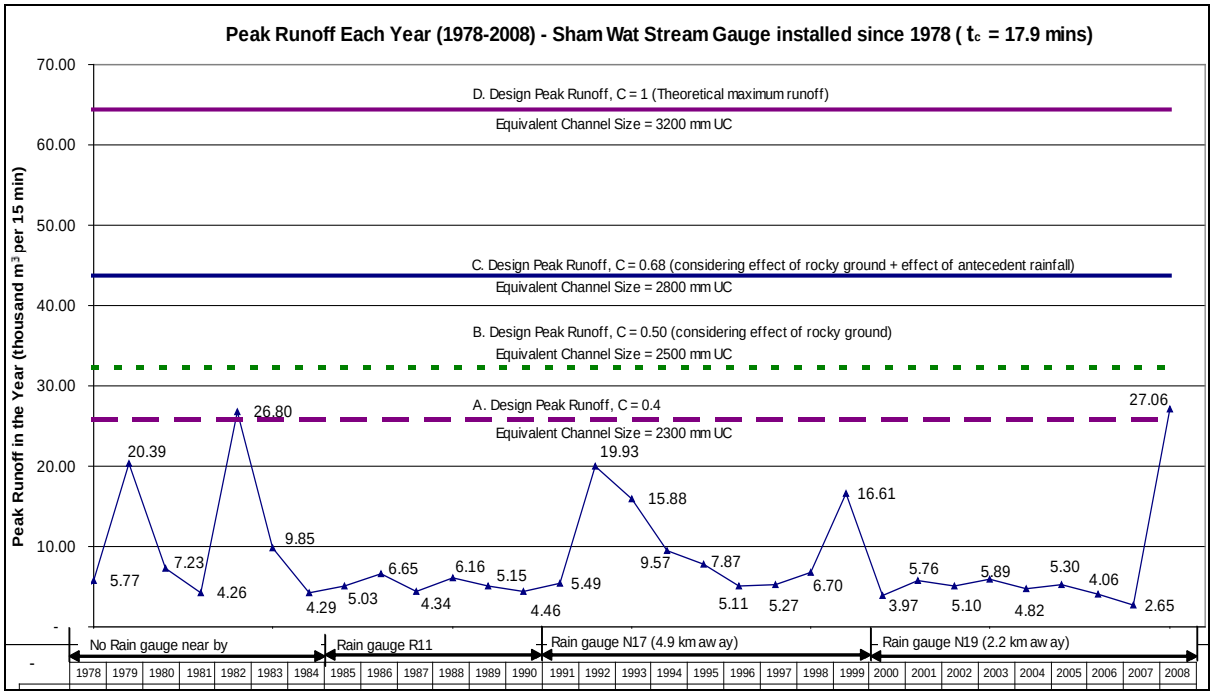


Figure E1 Maximum Peak Runoff Observed at Sham Wat Watershed, Compared with the Design Runoff Incorporating the Rocky Land Effect and the Effect of Antecedent Rainfall

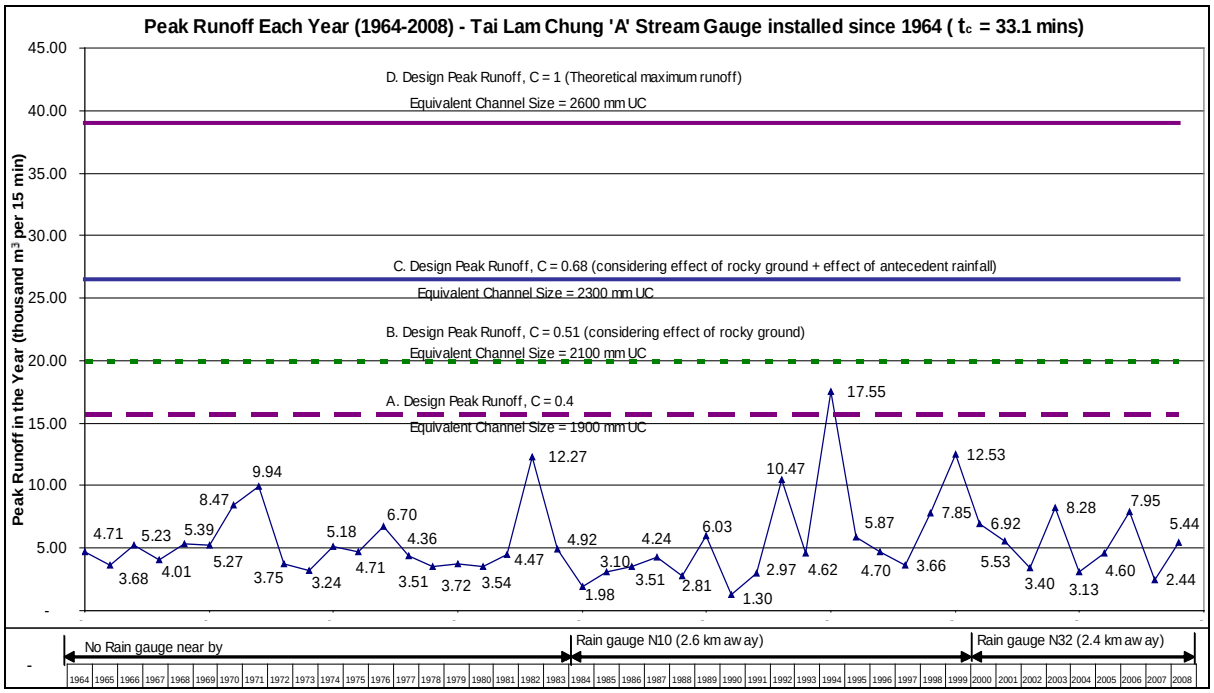


Figure E2 Maximum Peak Runoff Observed at Tai Lam Chung 'A' Watershed, Compared with the Design Runoff Incorporating the Rocky Land Effect and the Effect of Antecedent Rainfall

Table of Contents
Table of Contents
Table of Contents
Table of Contents

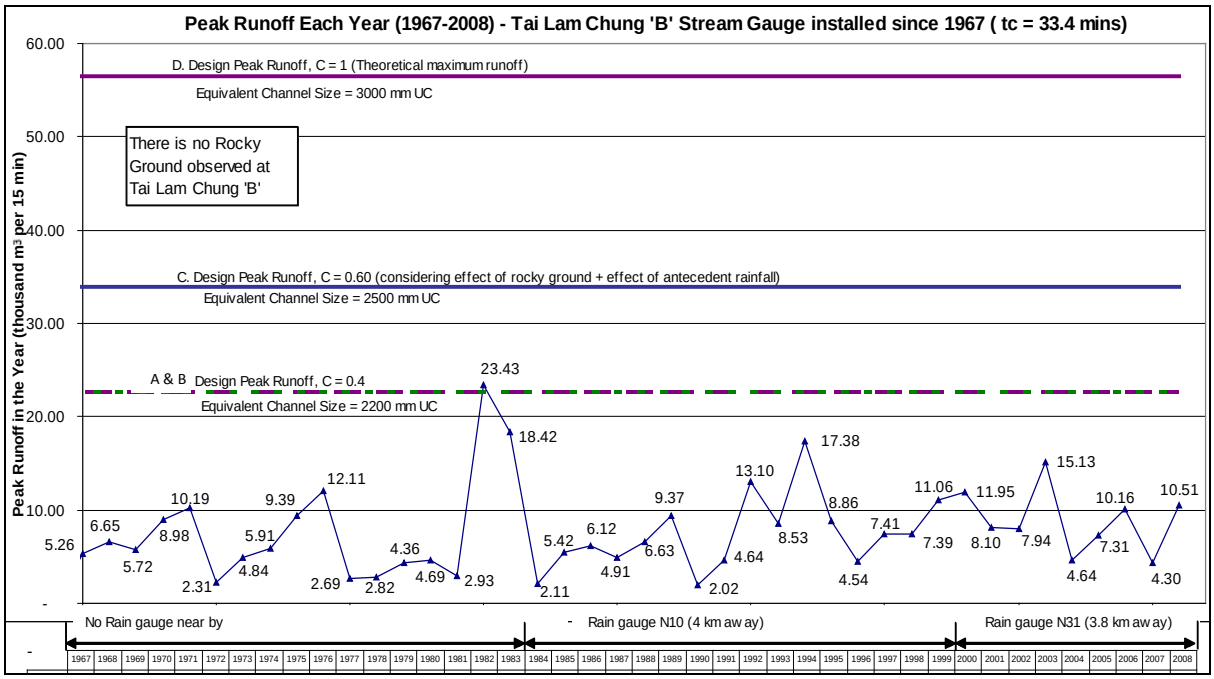


Figure E3 Maximum Peak Runoff Observed at Tai Lam Chung 'B' Watershed, Compared with the Design Runoff Incorporating the Rocky Land Effect and the Effect of Antecedent Rainfall

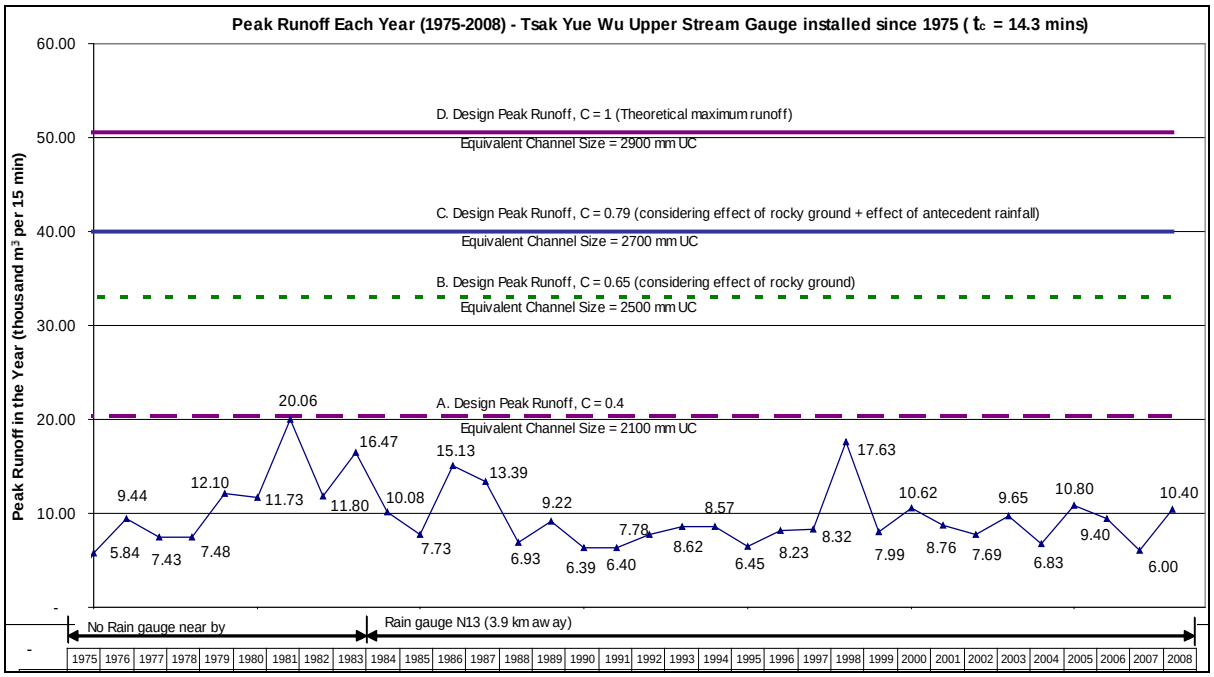


Figure E4 Maximum Peak Runoff Observed at Tsak Yue Wu Upper Watershed, Compared with the Design Runoff Incorporating the Rocky Land Effect and the Effect of Antecedent Rainfall

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Appendix F

Worked Example on Runoff Estimation Using the Recommended Approaches

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FUGRO (HONG KONG) LIMITED
7/F., Guardian House,
32 Oi Kwan Road,
Wanchai, Hong Kong

CONSULTING ENGINEERS
Tel : 2577-9023
Fax : 2895-2379 / 2895-3499
E-mail : fugro@fugro.com.hk

Job	Reference	Drawing reference	Calculations by	Checked by	Page
	090071	-	KCS	KKP	1
	Subject: Runoff Estimation for NTHM - Sham Wat				Date: 08/2012

1.0 Design Return Period

1.1 Slope drainage is designed to a frequency of 1 in 200 rainfall return period.

2.0 Time of Concentration

2.1 Time of concentration is calculated based on the modified form of Bransby-Williams Equation:

$t_c = 0.14465 \times L / (H^{0.2} \times A^{0.1})$

Eqn. 8.2 Geotechnical Manual for Slopes

where t_c = time of concentration (min) ,
A = area of catchment (m^2) ,
H = average fall (m per 100m) from the summit of catchment to the point of design
L = distance in metre measured on the line of natural flow between the design section and that point of catchment from which water would take the longest time to reach the design section (m)

2.2 Time of flow is calculated based on the open channel flow equation:

$V = K_u/n \times R^{2/3} \times S^{1/2}$

where V = flow velocity (m/s),
K_u = units conversion factor equal to 1
n = roughness coefficient
R = hydraulic radius (m)
S = slope (m/m)

t_f = channel flow length / flow velocity

Note : Therefore,

Overall Time of Concentration = time of concentration (for natural terrain) + time of flow in natural drainage channel

i.e. $t = t_c + t_f$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FUGRO (HONG KONG) LIMITED
7/F., Guardian House,
32 Oi Kwan Road,
Wanchai, Hong Kong

CONSULTING ENGINEERS
Tel : 2577-9023
Fax : 2895-2379 / 2895-3499
E-mail : fugro@fugro.com.hk

Job	Reference	Drawing reference	Calculations by	Checked by	Page
	090071	-	KCS	KKP	2
	Subject: Runoff Estimation for NTHM - Sham Wat				Date: 08/2012

2.3 Time of concentration by Bransby-Williams Equation

Sub-catchment Area

A' = 133,000 m^2 ; L = 620 m

Catchment Area
See Annex A

δh = 486 - 237
= 249 m

H = 40.2 m (average fall per 100m run)

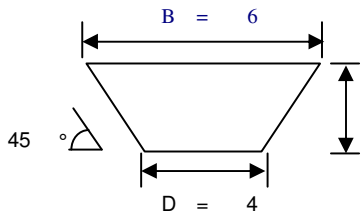
t_c = 0.14465 x 620 / ($40.2^{0.2}$ x $133000^{0.1}$)
= **13.167** mins

2.4 Time of concentration by open channel flow equation

V = $K_u/n \times R^{2/3} \times S^{1/2}$
V = 1/0.07*0.7^(2/3)*0.12^1/2
= 3.90 m/s

and the flow path w = 1115 m ;

t_f = channel flow length (w) / flow velocity (V)
t_f = 1115 / 3.9
t_f = **4.76** mins



natural channel cross section

δh = 237 - 103
= 134 m

S = 0.12 m n = 0.070

Assume channel side angle
= 45 °

D = 6 - 2 x sin 45°
= 4.0 m

A = (6+4.00) x 1/2
= 5 m^2

P = 6.828 m -> R = 0.7

Therefore, time of concentration is

t = $t_c + t_f$
t = 13.167+4.76
= **17.93** mins

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FUGRO (HONG KONG) LIMITED
7/F., Guardian House,
32 Oi Kwan Road,
Wanchai, Hong Kong

CONSULTING ENGINEERS
Tel : 2577-9023
Fax : 2895-2379 / 2895-3499
E-mail : fugro@fugro.com.hk

Job	Reference	Drawing reference	Calculations by	Checked by	Page
	090071	-	KCS	KKP	3
	Subject: Runoff Estimation for NTHM - Sham Wat				Date: 08/2012

3.0 Runoff Coefficient

3.1 Effect of Ground Properties:

Runoff coefficient for Rocky Ground = **0.9**
Runoff coefficient for other ground = **0.4**

Stormwater Drainage Manual, pg.35

Proportion of slope with Rocky Ground = **20%**
Proportion of slope other ground = **80%**

See Annex B

3.2 Effect of Antecedent Rainfall

For Rocky Ground : C = **1.0**

For Other Ground : C = 0.4 x (1 + 50%) **(with 50% increase in other ground)**
= 0.6

Runoff coefficient taking account of antecedent rainfall = 1.0 x 20% + 0.6 x 80%
= **0.68** <= 1 ok

4.0 Peak Runoff Estimation

4.1 Peak runoff is determined by the "Rational Method" using the following formula:

Eqn. 8.7 Geotechnical Manual for Slopes

$Q = Ci A / 60$

where Q = maximum runoff (litres/min)
C = runoff coefficient
i = design mean intensity of rainfall (mm/hr)
A = area of catchment (m^2)

C = 0.68 — See above

t = 17.93 mins — See page 2

i_{200} = 250 mm/hr — See GEO TGN 30

A = 1,030,000 m^2 — See Annex A

Q_{200} = 0.68 x 250 x 1030000 / 60
= **2,918,333** litres/min

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FUGRO (HONG KONG) LIMITED
7/F., Guardian House,
32 Oi Kwan Road,
Wanchai, Hong Kong

CONSULTING ENGINEERS
Tel : 2577-9023
Fax : 2895-2379 / 2895-3499
E-mail : fugro@fugro.com.hk

Job	Reference	Drawing reference	Calculations by	Checked by	Page
	090071	-	KCS	KKP	4
	Subject: Runoff Estimation for NTHM - Sham Wat				Date: 08/2012

Annex A - Catchment Area

Catchment Area (A) = 1,030,000 m^2
Sub-catchment Area (A') = 133,000 m^2

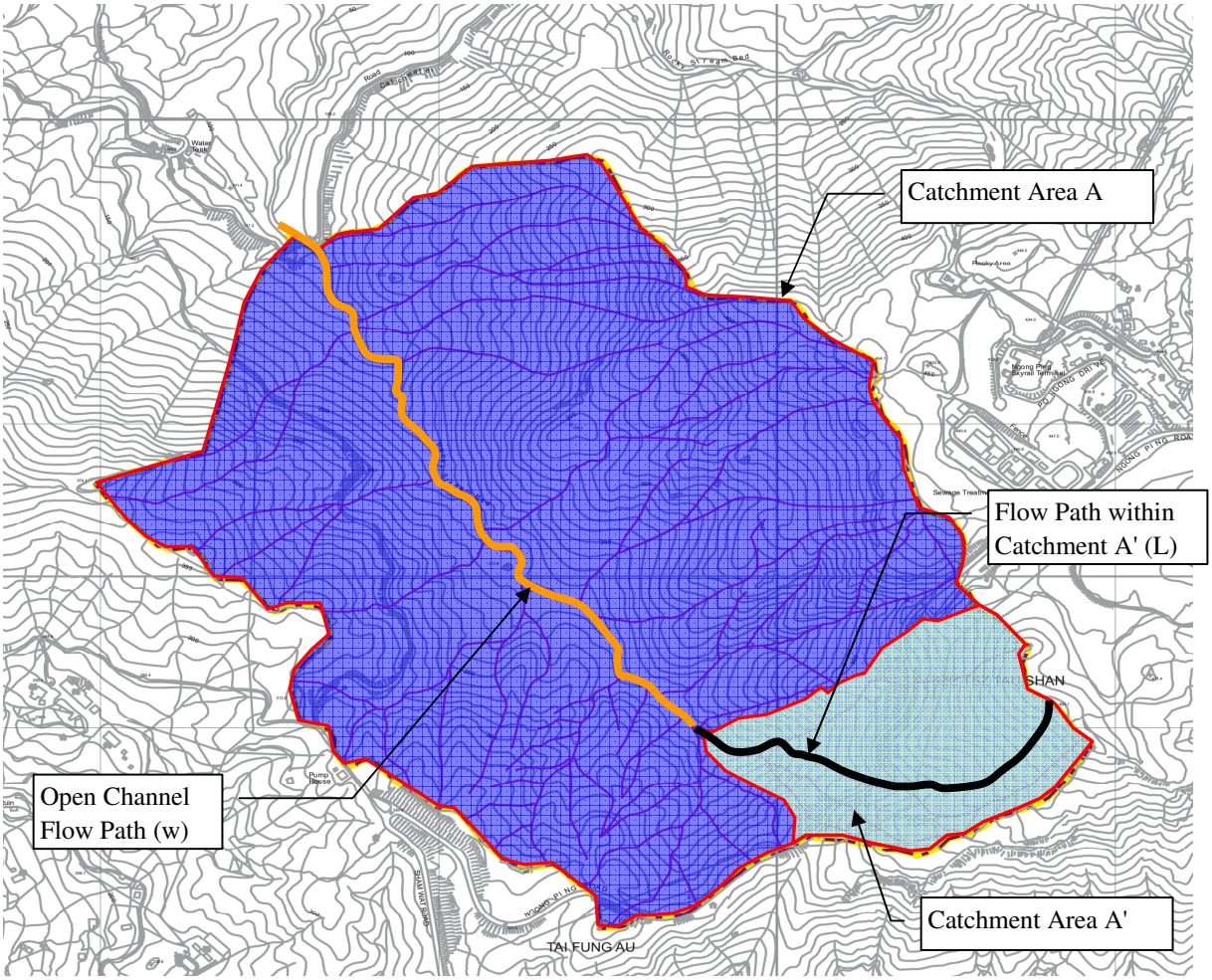


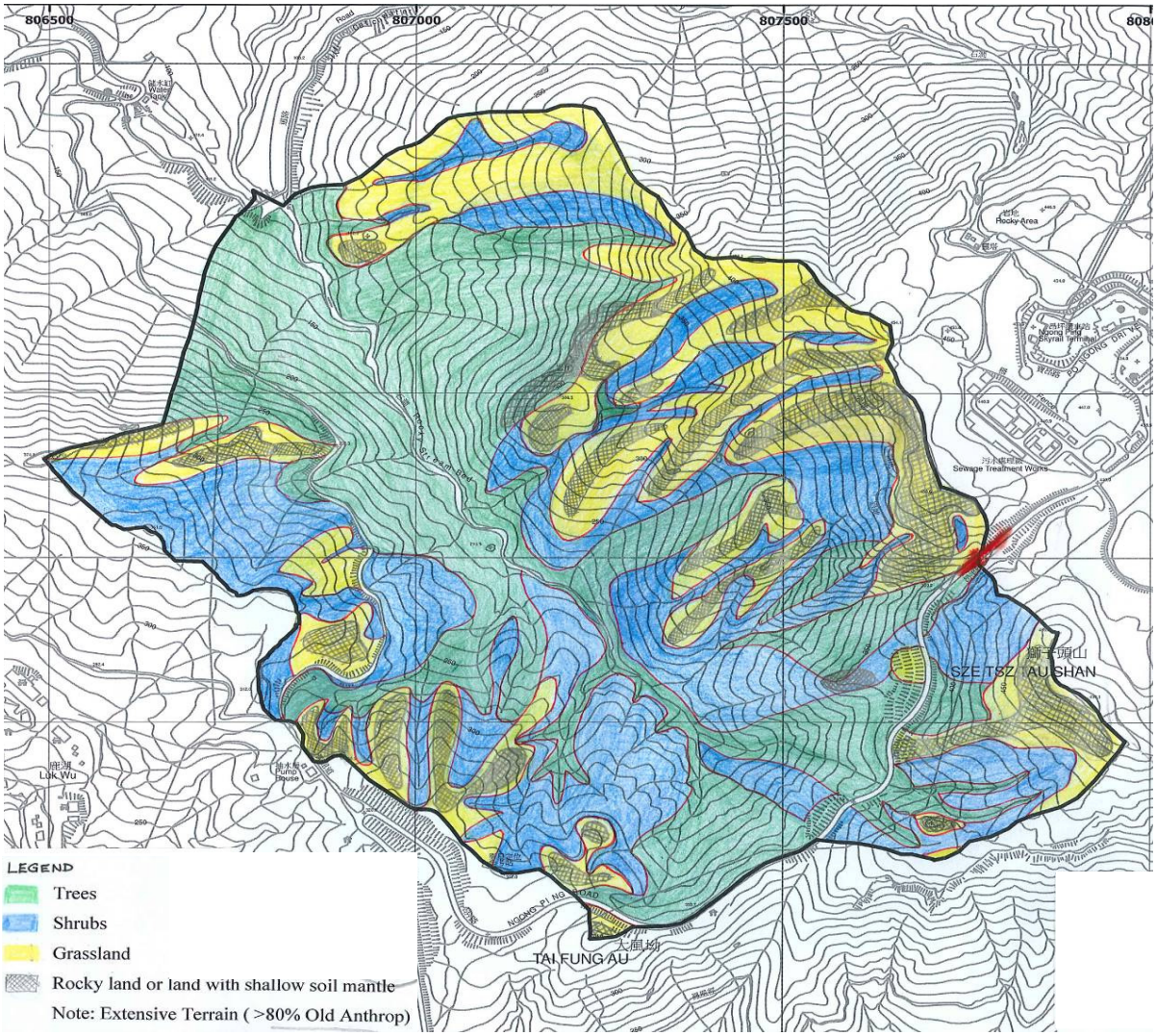
Table of Contents
Table of Contents
Table of Contents
Table of Contents

FUGRO (HONG KONG) LIMITED
7/F., Guardian House,
32 Oi Kwan Road,
Wanchai, Hong Kong

CONSULTING ENGINEERS
Tel : 2577-9023
Fax : 2895-2379 / 2895-3499
E-mail : fugro@fugro.com.hk

Job	Reference	Drawing reference	Calculations by	Checked by	Page
	090071	-	KCS	KKP	5
	Subject: Runoff Estimation for NTHM - Sham Wat				Date: 08/2012

Annex B - Surface Properties



Sham Wat

Catchment Size	=	1,030,000	m^2
Longest Flow Path	=	1735	m
Old Terraces	=	0%	
Grassland	=	8%	
Trees and Shrubs	=	72%	
Rocky Ground	=	20%	

Table of Contents
Table of Contents
Table of Contents
Table of Contents

GEO PUBLICATIONS AND ORDERING INFORMATION
土力工程處刊物及訂購資料

A selected list of major GEO publications is given in the next page. An up-to-date full list of GEO publications can be found at the CEDD Website http://www.cedd.gov.hk on the Internet under "Publications". Abstracts for the documents can also be found at the same website. Technical Guidance Notes are published on the CEDD Website from time to time to provide updates to GEO publications prior to their next revision.

部份土力工程處的主要刊物目錄刊載於下頁。而詳盡及最新的土力工程處刊物目錄，則登載於土木工程拓展署的互聯網網頁 http://www.cedd.gov.hk 的"刊物"版面之內。刊物的摘要及更新刊物內容的工程技術指引，亦可在這個網址找到。

Copies of GEO publications (except geological maps and other publications which are free of charge) can be purchased either by:

Writing to
Publications Sales Unit,
Information Services Department,
Room 626, 6th Floor,
North Point Government Offices,
333 Java Road, North Point, Hong Kong.

or

- Calling the Publications Sales Section of Information Services Department (ISD) at (852) 2537 1910
- Visiting the online Government Bookstore at http:// www.bookstore.gov.hk
- Downloading the order form from the ISD website at http://www.isd.gov.hk and submitting the order online or by fax to (852) 2523 7195
- Placing order with ISD by e-mail at puborder@isd.gov.hk

讀者可採用以下方法購買土力工程處刊物(地質圖及免費刊物除外):

書面訂購
香港北角渣華道333號
北角政府合署6樓626室
政府新聞處
刊物銷售組

或

- 致電政府新聞處刊物銷售小組訂購 (電話：(852) 2537 1910)
- 進入網上「政府書店」選購，網址爲 http://www.bookstore.gov.hk
- 透過政府新聞處的網站 (http://www.isd.gov.hk) 於網上遞交訂購表格，或將表格傳真至刊物銷售小組 (傳真：(852) 2523 7195)
- 以電郵方式訂購 (電郵地址：puborder@isd.gov.hk)

1:100 000, 1:20 000 and 1:5 000 geological maps can be purchased from:

Map Publications Centre/HK,
Survey & Mapping Office, Lands Department,
23th Floor, North Point Government Offices,
333 Java Road, North Point, Hong Kong.
Tel: (852) 2231 3187
Fax: (852) 2116 0774

讀者可於下列地點購買1:100 000、1:20 000及1:5 000地質圖：

香港北角渣華道333號
北角政府合署23樓
地政總署測繪處
電話: (852) 2231 3187
傳真: (852) 2116 0774

Requests for copies of Geological Survey Sheet Reports and other publications which are free of charge should be directed to:

For Geological Survey Sheet Reports which are free of charge:
Chief Geotechnical Engineer/Planning,
(Attn: Hong Kong Geological Survey Section)
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5380
Fax: (852) 2714 0247
E-mail: jsewell@cedd.gov.hk

For other publications which are free of charge:
Chief Geotechnical Engineer/Standards and Testing,
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5346
Fax: (852) 2714 0275
E-mail: florenceko@cedd.gov.hk

如欲索取地質調查報告及其他免費刊物，請致函：

免費地質調查報告:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
規劃部總土力工程師
(請交:香港地質調查組)
電話: (852) 2762 5380
傳真: (852) 2714 0247
電子郵件: jsewell@cedd.gov.hk

其他免費刊物:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
標準及測試部總土力工程師
電話: (852) 2762 5346
傳真: (852) 2714 0275
電子郵件: florenceko@cedd.gov.hk

MAJOR GEOTECHNICAL ENGINEERING OFFICE PUBLICATIONS
土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 302 p. (English Version), (Reprinted, 2011).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2007).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.
Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.
GEO Publication No. 1/2007	Engineering Geological Practice in Hong Kong (2007), 278 p.
GEO Publication No. 1/2009	Prescriptive Measures for Man-Made Slopes and Retaining Walls (2009), 76 p.
GEO Publication No. 1/2011	Technical Guidelines on Landscape Treatment for Slopes (2011), 217 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents