# RAINSTORM RUNOFF ON SLOPES

GEO REPORT No. 12

J. Premchitt, T.S.K. Lam, J.M. Shen & H.F. Lam

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
HONG KONG

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# PREFACE

In keeping with our policy of releasing information of general technical interest, we make available some of our internal reports in a series of publications termed the GEO Report series. The reports in this series, of which this is one, are selected from a wide range of reports produced by the staff of the Office and our consultants.

Copies of GEO Reports have previously been made available free of charge in limited numbers. The demand for the reports in this series has increased greatly, necessitating new arrangements for supply. In future a charge will be made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents and presents the results of research work of general interest in GEO Publications. These publications and the GEO Reports are disseminated through the Government's Information Services Department. Information on how to purchase them is given on the last page of this report.

A. W. Malone
Principal Government Geotechnical Engineer
April 1995

## EXPLANATORY NOTE

This GEO Report consists of two Special Project Reports on rainstorm runoff and infiltration on slopes in Hong Kong.

They are presented in two separate sections in this Report. Their titles are as follows :

# SECTION 1 : RAINSTORM RUNOFF ON SLOPES

J. Premchitt, H.F. Lam & J.M. Shen

This report was originally produced as GCO Special Project Report No. SPR 5/86

# FOREWORD

This report evaluates the effectiveness of various types of slope surface cover in generating rainstorm runoff. It is based on field measurements at seven man-made slopes over a period of two years. Field monitoring of these slopes is continuing at the present time.

The Highways Department, Architectural Services Department and Agriculture and Fisheries Department provided assistance to this study. M.G. Anderson, R.W. Lumsdaine and G.E.B. Choot contributed to the project in the very early stages.

J.B. Massey

J.B. Massey
Chief Geotechnical Engineer/Special Projects

# CONTENTS

# 1. INTRODUCTION

The incidence of slope failures in Hong Kong during periods of intense rainstorm indicates the degree to which rainfall, and subsequent infiltration and groundwater changes, affect slope stability. Estimation of the rate and amount of rainfall infiltration is very important in the analysis and design of slopes. However, relevant field data are very sparse in Hong Kong, particularly for man-made (cut and fill) slopes (GCO, 1984).

In 1983 a consultant to the Geotechnical Control Office (GCO), M.G. Anderson of Bristol University, completed a study on soil suction in slopes in Hong Kong and recommended further detailed field study of runoff and infiltration on selected man-made slopes (Anderson, 1983). His report showed that there was very little existing information relevant to local conditions. Study was required, therefore, to obtain quantitative data on runoff and infiltration for different types of slope surface cover. These data would enable an accurate estimation of the changes in groundwater conditions, including suction, in relation to rainfall amounts.

This study commenced in late 1983, in accordance with the recommendation. Instrumentation of five slopes was completed in 1984 and collection of the field data was initiated in the wet season of that year. Data were obtained from a total of seven slopes in 1985. The progress of the study has been presented in a number of interim reports issued since late 1983. The present report summarizes all of the results up to the end of 1985. Field monitoring of these slopes is continuing at the present time.

Assessment of rainfall infiltration is important in the analysis and design of slopes. However, infiltration cannot be readily measured directly in the field. A practical approach is to estimate the infiltration from recorded rainfall and runoff. After subtraction of runoff from storm rainfall, the amount left is the potential infiltration. This amount may be taken as the actual infiltration if the small initial abstraction at the slope surface is ignored. It should be emphasized, however, that the actual infiltration is always less than the potential.

This study is mainly concerned with rainfall and runoff measurements made during a two-year period at seven man-made slopes. The field data have been analysed using similar approaches to those of previous studies in Hong Kong and elsewhere, to enable a direct comparison of the results. The relationships developed here may be used for the estimation of runoff and infiltration on slopes with various types of surface cover, and subject to a range of rainfall conditions.

# 2. PREVIOUS STUDIES

## 2.1 General

The disposition of storm rainfall after the rain water has reached the ground in the general situation is shown in Figure 1. These components of rainfall may be divided into three groups : initial abstraction, infiltration and runoff. They are discussed below. The relevant mathematical expressions are given in Appendix B.

### 2.1.1 Initial Abstraction

The term initial abstraction includes interception by vegetation and depression storage at the ground surface, see Figure 1.

Interception was studied in detail by Horton (1919) and Butler (1957) among others, and a good review was provided by Penman (1963). Interception is dependent on species and density of vegetation, antecedent rainfall and rainfall amount. It is normally high in forests and low on grass lands. The actual amount cannot be precisely measured in the field but values have been estimated at from less than 5% to more than 40% of the rainfall amount in various situations (Penman, 1963, Baver et al, 1972, Linsley et al, 1982, Rethati, 1983 and Wilson, 1983); for very light rain, it can of course be close to 100%.

The depression storage is filled rapidly and the filling rate at high rainfall is almost zero. Because of the wide variability of depressions and the general lack of experimental data, a generalized relation or model of the process does not exist (Overton & Meadows, 1976; Linsley et al 1982). However, an empirical equation is often used, see Appendix B.2. Reported values of depression storage are in the range of 2.5 to 5.0 mm for various types of soil (Overton & Meadow, 1976).

For the slopes studied in this report, the initial abstraction is considered to be small.

### 2.1.2 Infiltration

Infiltration can be divided into three parts : that which is retained locally, and that which is transported as interflow and as groundwater flow. The latter two parts eventually join the total runoff in streams and rivers. In this study, however, runoff has been measured immediately adjacent to small catchments. Therefore, there is negligible contribution from interflow or groundwater flow to the measured runoff. Also, over the duration of a rainstorm, it is estimated that most of the infiltration will be retained locally, altering soil suction and local groundwater levels. This is considered to be the most important cause of rapid landslides in Hong Kong (Brand et al, 1984; Premchitt et al, 1985). Over an extended time period after rain, the water will either evaporate into the atmosphere or drain away as interflow or groundwater flow.

The infiltration process can be studied by field infiltration tests (GCO, 1984), and a typical result is shown in Figure 2. The curve for the infiltration rate in Figure 2(b) represents the maximum time-dependent infiltration capacity of the soil, since there is an unlimited supply of water in the test. Infiltration curves for some typical soils are illustrated in Figure 3. Generally, the infiltration rate is very high at the start of the test and decreases gradually with time to a final constant value. Figure 3 shows limiting rates of about 5 to 40 mm/hr, but rates could be higher for soils with grass surface cover. Theoretical studies were carried out to explain and predict this behaviour, including the wetting front approach (Green & Ampt, 1911; Lumb, 1962), semi-empirical approach (Horton, 1939; Holtan, 1961; Musgrave & Holtan, 1964; SCS, 1972), diffusion theory (Phillip, 1960; Lumb, 1962) and computer numerical model simulation (Freeze, 1969, 1980; Anderson, 1983). A good review was provided by Hillel (1971, 1982). Some mathematical relations from these theories are given in Appendix B.3.

In an actual rainstorm, the infiltration rate will be less than those given by infiltration curves if the rate at which rain water is supplied is less than the capacity.

### 2.1.3 Runoff

Accurate runoff measurement in the field can readily be made, in contrast to the crude determination of other components. As stated in Section 2.1.2, this study is mainly concerned with rainstorm runoff which has no contribution from interflow or groundwater flow. Various theories for the estimation of runoff are discussed in Section 2.2.

Rainfall must satisfy the capacity for interception, depression storage and infiltration before a significant runoff can be produced (Overton & Meadows, 1976; Linsley et al, 1982). The variation with time of the rate and cumulative amounts of the above three main components are shown in Figure 4 for a constant rate of rainfall. The initial abstraction will consume most or all of the initial rainfall, but will be insignificant at higher rainfall. Infiltration will be large initially and gradually decline to a low constant rate at high rainfall. Because the rainfall is largely absorbed by these two processes initially, there is a very small runoff at the start of rainstorm or for a light rain event. At higher rainfall, there will be more runoff at a rate which is lower than the rainfall intensity, and the loss at this time will be the infiltration at the (constant) limiting rate.

The time scale in Figure 4 can also be considered the scale for rainfall amount, since a constant rate of rainfall is assumed. The runoff curve in Figure 4, therefore, may be taken as a prediction of the rainfall-runoff relationship. This relationship will be discussed in subsequent sections.

## 2.2 Runoff Models

### 2.2.1 $\phi$-index

This model assumes that the lumped capacity for rate of initial abstraction plus infiltration remains constant throughout the rainstorm period. The $\phi$-index is the rainfall intensity above which rain will run off and below which the rain will be totally absorbed by initial abstraction and infiltration, see Figure 5(a). This is of course a very crude approximation, considering the actual time-variations discussed above. However, it has often been used in engineering applications in conjunction with unit hydrograph analysis (Government of Hong Kong, 1968; Linsley et al, 1982; Shaw, 1983). This is also the model discussed in the Geotechnical Manual for Slopes (GCO, 1984) see Figure 5(b).

The W-index method is a refinement of this approach, in which the interception and depression storage are subtracted from the $\phi$-index. It is doubtful whether this method will provide a more significant parameter than the simpler $\phi$-index (Linsley et al, 1982).

The $\phi$-index method assumes a sudden change from no runoff to full runoff when the intensity exceeds the $\phi$-index value. An assumption of a more gradual change may represent the actual runoff process more closely. This new approach has been attempted in Section 4.2.

### 2.2.2 Multi-variable Relationships

Runoff is obviously dependent on the rainfall amount, but other factors may have additional effects to some degree. Empirical correlations on the basis of field data have been established (Linsley et al, 1982). The factors included are antecedent rainfall, the time of the year (seasonal effects), rainfall duration and rainfall amount. The prediction of runoff can be made by means of coaxial correlation charts in a step-by-step procedure, see Linsley et al (1982). It should be emphasized, however, that the charts were devised from a set of observed data in a particular locality, and should not be taken to represent all slopes. There are also other statistical studies resulting in multi-variable linear regression equations for the prediction of runoff, such as Osborne & Lane (1969) and Hsu et al (1983). These were based on mathematical relationships of a set of measured data, without any explanation of the physical significance of the equations.

### 2.2.3 Rainfall-Runoff Relationships

A simple and direct rainfall-runoff relationship could perhaps closely represent the actual runoff processes. Figures 6(a) to 6(c) show the relationship for three natural catchments in the USA and UK. The runoff curves show the characteristics discussed in Section 2.1.3, namely the initial loss at low rainfall and increasing runoff at higher rainfall. Most of the losses are infiltration. Figures 6(c) and 6(d) show the possible influence of andecedent soil moisture conditions on the runoff curves. This is a simple version of the multi-variable relations discussed previously. The antecedent soil moisture conditions may also be expressed in terms of cumulative antecedent rainfall.

This simple relationship was developed and established for a great variety of catchments by the Soil Conservation Service of the US Department of Agriculture (SCS, 1972; discussed in Overton & Meadows, 1976; Raudkivi, 1979; and Hawkins et al, 1985). This semi-empirical method is based on the assumption that the ratio of runoff to the rainfall in excess of initial abstraction is equal to the ratio of rainwater retained in the soil to the potential maximum retention. The relevant mathematical expressions are given in Appendix B.4. On the basis of this assumption, a series of runoff curves with different curve numbers (CN) was established for different types of runoff catchment area. This is shown in Figure 7. The values of CN are dependent on the potential maximum retention of the area, see also Appendix B.4.

SCS (1972) provided lists of CN values for various catchment areas having different soil types, land uses (types of surface cover), and antecedent rainfall conditions. Some of these lists are provided in Appendix B. This curve number technique has been used extensively in hydrological studies (Overton & Meadows, 1976). The technique has been verified by Hjelmfelt (1980b), extended for varying site moisture cases (Hawkins, 1978), used to estimate infiltration (Aron et al, 1977; Hjelmfelt, 1980a) and employed to investigate probability of extreme runoff (Hawkins et al, 1985). Bondelid et al (1981) discussed the estimation of CN from remote sensing data.

It is prudent not to apply this technique directly to local conditions without first verifying it by actual runoff measurements. The literature on this technique should be treated as a good collection of empirical data, showing patterns of runoff production and providing a first approximation of runoff.

## 2.3 Studies in Hong Kong

The Water Authority (now Water Supplies Department) compiled and analysed rainfall-runoff data, which were recorded from the 1950s onwards, for a number of Hong Kong natural catchments as a part of the report on design floods for Hong Kong (Government of Hong Kong, 1968). Flows were measured by means of compound weirs and broad-crested weirs. Runoff data from eight catchment areas were analysed using the ø-index method, in conjunction with unit hydrograph analysis. The Geotechnical Manual for Slopes (GCO, 1984) adopted the results from the ø-index analysis (Figure 5(b)) and suggested that 50% of the rainfall is produced as runoff and 50% as infiltration. The Water Supplies Department continue to monitor runoff at a number of natural catchments, and issue the annual data compilation in 'Hong Kong Rainfall and Runoff'.

As a part of the Mid-levels Study (GCO, 1982a), runoff was measured at thirteen natural catchments in the Mid-levels area. Runoff was measured by weirs, some of which were calibrated. The data were collected for 1980 only, and were limited, since that year was exceptionally dry (GCO, 1982a). The study incorporated the data from the previous study (Government of Hong Kong, 1968) and derived a storm loss (rainfall minus runoff) of about 66%.

The Department of Geography, Chinese University of Hong Kong, carried out a runoff study on two small cut slopes within the campus, with chunam and grass surface covers respectively, and the results were reported by Hsu et al (1983). The study areas were 49 and 65 $m^2$ respectively, with slope angles of $45^{\circ}$ and $40.5^{\circ}$. A small cylindrical tank with a V-shaped slot, at an angle of only $2.1^{\circ}$, was used to measure the runoff. There is no evidence in the report of calibration of the weir. The data were collected in 1981, and during one month in 1982. Only a few heavy rainfall events were recorded; the maximum rainfall was 108 mm. About 70% of all the 52 recorded events had rainfall amounts less than 10 mm. Statistical analysis showed strong correlation between runoff and rainfall amount, but rather poor correlation with duration and intensity. Multiple regression equations were established, and are given in Table 1. These must be viewed with caution due to the limitations mentioned above.

The results from the above three studies have been replotted to show the rainfall-runoff relationships in Figure 8. This figure should be compared with Figures 6 and 7. It can be observed that there is a large initial loss with almost no runoff, and an increasing runoff at higher rainfall. For natural catchments and the grass-covered cut slope, there was almost no runoff for events with rainfall of less than 40 mm. These characteristics are similar to those discussed in Section 2.1.3 and shown in Figure 4.

## 3. FIELDWORK

### 3.1 Site Description

The sites were selected early in the study programme, mainly to satisfy the requirement for a wide range of surface cover types. Six weathered granite cut slopes and one compacted volcanic soil fill slope were selected. The six granite cut slopes are grouped in three pairs at three sites : Clear Water Bay Road, Tsuen Wan and Chuk Yuen. The volcanic fill slope is a part of a high bund constructed on the periphery of the proposed Kohima Barracks in Sai Kung. A location map of these slopes is given in Figure 9, and relevant information on the slopes is provided in Table 2. They consist of one chunammed slope, one hydroseeded grass slope, three turfed grass slopes (one of them the compacted fill slope) and two with dense tree cover. The species of vegetation on these slopes have been identified by the Agriculture and Fisheries Department. Recent photographs of the slopes are given in Plates 1 to 7. A detailed plan for each of the slopes is provided in Figures 10 to 15.

The slopes are rectilinear in plan, have low water tables and relatively large catchment areas (260 to 710 $m^2$). They already have well-defined drainage systems consisting of stepped channels and U-channels. They have no horizontal drains or other subsurface drainage measures which could alter the normal groundwater conditions. The slopes were all formed within four years prior to the beginning of the study in 1983.

The two slopes on Clear Water Bay Road, one with chunam cover and one with grass cover, were the sites for the soil suction study (Anderson, 1983). The runoff plots on these two 20 m high slopes are the middle portions, about 8 m high, located between two berms, see Figures 10 and 11. There are some trees on the grassed slope (Plate 2). The grass cover on this slope is less uniform than on the other slopes. The two slopes are about 200 m apart.

Both slopes in Tsuen Wan have dense tree cover. The trees on slope TWA are taller, about 3 to 5 m high, while those on slope TWB are about 2 to 3 m high. Both runoff plots cover the full height of the cut slopes except for the lowest parts, see Figures 12 and 13. The slopes are less than 200 m apart.

The two grassed slopes at Chuk Yuen are contiguous. One of them was hydroseeded (CYA) and the other was turfed (CYB). The runoff plots cover the full height of both slopes, see Figure 14. The compacted fill slope KOH has the largest catchment area (710 $m^2$). There are a number of scattered trees (less than 2 m high) on the slope. The runoff plot covers all of the slope except for the lowest portion, see Figure 15. These three slopes were formed just prior to 1983.

An attempt was made to quantify the density of trees, shrubs and grass, and the state of chunam on these slopes, so that an accurate comparison of surface cover conditions could be made. The results of the field survey are given in Table 3. The average spacings of trees and shrubs are accurate because they could be counted. By its nature, the estimate of grass density is not accurate in absolute terms, but the relative comparison between slopes is considered reliable. The highest grass density is on slope KOH and the lowest is on slope CYB. The grass density on hydroseeded slope CYA is clearly higher than that on the adjacent turfed slope CYB.

The tree spacings on the two slopes TWA and TWB are about 2 m, indicating that the slopes are almost fully covered with tree canopy, see Plates 3 and 4. The species of vegetation for each slope are listed in Table 4.

The chunam condition on slope CWA may be classified as poor on the scale of bad-poor-average used in the CHASE study (GCO, 1982b) and by Anderson (1983). There are some cracks on the chunam surface but most of them are fine; the openings are generally less than 0.5 mm.

A limited number of field infiltration and permeability tests were carried out to determine the soil permeability at these sites. For the weathered granite slopes, the permeability values are similar and fall in the range 20 to 55 mm/hr ($6$ to $15 \times 10^{-6}$ m/s). The permeability for the volcanic fill slope KOH is substantially lower, being about 6.4 mm/hr ($1.8 \times 10^{-6}$ m/s).

## 3.2 Instrumentation

A detailed topographic survey was carried out at each site by the GCO Survey Section. The survey established the surface drainage patterns and the flow directions in drainage channels, and defined the catchment area and its perimeter. The survey resulted in the site plans given in Figures 10 to 15. Where necessary, the existing drainage pattern was modified to achieve the desired extent of runoff plot. The modifications included construction of cut-off walls, drainage divides, new U-channels, by-pass channels and improvements to existing surface covers, berms and channels. Hydroseeding and turfing for the slopes at Chuk Yuen were also carried out as part of this study. A stilling basin was constructed at each slope to form part of the runoff measuring equipment. The fieldwork was carried out by the Highways Office (now the Highways Department) and the Architectural Office (now the Architectural Services Department) under the coordination of the Special Projects Division, GCO.

The details of the stilling basin, including the V-notch weir, are shown in Figure 16. A Clarke automatic water level recorder with a one revolution per day clock was used at each site. Seven-day clocks were used at most sites initially, but by early 1985 these were all replaced by one-day clocks to improve the resolution of the time scale. The water level (stage) was recorded directly on a graph sheet, with a total range of 225 mm. The time scale on the graph was 3.3 minute per mm. There were some problems with the stage rods initially, but these were resolved later on.

The thin steel-plate V-notch weirs were constructed locally. The weir angles varied from 17° for the Clear Water Bay slopes to 65° for the Kohima Barracks slope. The variations were to take account of the different sizes of the respective runoff catchment areas. For a first approximation, the runoff flow rates may be calculated from a standard theoretical weir equation, see Appendix B.5. However, for the accuracy required in subsequent correlation analyses, it was necessary to calibrate these weirs, particularly for the condition where the water flows through both the stilling basin and the weir. The calibrations were carried out on site. The results are discussed in Appendix C and summarised in Table 5. In a trial calculation, it was found that the use of the theoretical equation produced errors and inconsistencies. Therefore the weir constants derived from the calibrations have been used throughout this report to calculate runoff.

The data from nearby GCO automatic raingauges were used directly in the analysis. At Chuk Yuen and Tsuen Wan, where the existing raingauges were relatively far away (about 1.0 km), autographic gauges were installed near the sites in June 1985. In all cases, the distance to the closest raingauge is less than 250 m. The autographic raingauge used is the Casella tilting-siphon gauge, using a graph sheet on a drum with a one-day clock. The resolution of the rainfall data for both types of raingauge is 0.5 mm.

### 3.3 Data Collection

The 15-minute rainfall was taken as the basic unit for all analyses. For each rainfall event, a series of 15-minute rainfall data for the relevant time period was extracted and entered into a computer.

Field visits were made once a week during the wet seasons to collect runoff data at all sites and to collect rainfall data from the autographic raingauges, this frequency being required to rewind the clocks. Since the clock rate was one revolution per day, the graph sheets showed seven traces of record for the seven days. Estimation of rainfall and runoff from these graph sheets could then be made in the office.

## 4. MONITORING RESULTS AND ANALYSIS

### 4.1 Runoff Determination

Determination of runoff and all subsequent analyses were carried out on the Government Data Processing Agency mainframe computer ICL 2988, via the terminals in the GCO.

The runoff hydrographs collected from the sites were digitized into a series of coordinates (time, stage), and the runoff was calculated from these coordinates. The runoff was computed using the method given in Appendix B.5 and the weir constants derived from field calibration, given in Appendix C. Runoff hydrographs for two adjacent rainstorms were separated by adopting a cut-off at the very low stage level of 5 mm.

Selected rainfall events were used in the analysis. Some events did not have adequate records and so had to be excluded. The statistics of the rainfall events used at the four locations are given in Figures 17 to 20. The distribution of the number of events with respect to rainfall amount, maximum intensity, duration and 5-day antecedent rainfall are shown in these figures. A total of 45 to 58 events were used for all of the slopes except those at Tsuen Wan, where the data were available for 1985 only. In any typical year, there will be only a few heavy rainstorm events with a high probability of landslides, while there will be a very large number of light rain events (Premchitt, 1986). The heavy rainstorm events obviously are of most interest to the engineer. For this two-year study period, two to six heavy rainstorms each having rainfall greater than 100 mm, and a maximum of 276 mm, were included in the analysis at each location. This should be compared with 394 mm for the major rainstorm on 29 May 1982 (Brand et al, 1984). Most of the events with rainfall greater than 50 mm were included in this data set; while it contained a smaller proportion of lighter rain events.

Appendix A summarises all of the basic rainfall data and the calculated runoff data obtained in the study. It also shows the runoff coefficient, which is a simple ratio of runoff to rainfall. It should be noted that while runoff was measured from large catchment areas, rainfall was measured from raingauges with an opening of only 200 mm diameter. This unavoidable incompatibility could be one of the reasons for the random scattering around a common trend in the subsequent analyses.

Figure 21 shows a typical time distribution of rainfall and runoff, and enables a direct comparison between the runoff responses of the chunammed slope CWA and the grassed slope CWB. For the grassed slope, there is evidence of a large initial loss with very little runoff until cumulative rainfall is greater than 20 mm. The effects on the chunammed slope are much less pronounced.

## 4.2 Ø-index Analysis

The Ø-index method has been discussed in Section 2.2.1. For each rainstorm event, the total rainfall in excess of a chosen intensity (Ø-index) was calculated iteratively with different Ø-index values until it was within 1.0% of the actual measured runoff. The series of 15-minute rainfall data were used in the calculation.

The Ø-index values are plotted against total rainfall for all slopes in Figures 22 and 23. The scattering of data could be due to the very crude assumption of a constant maximum loss rate. However, for all cases the Ø-index rarely exceeds 40 mm/hr. The average value of all events for each slope also appears to be a good indicator of the relative imperviousness of the cover when a comparison is made between slopes, see Table 6. The average for the chunammed slope CWA is only 1.8 mm/hr, in comparison with 16.9 mm/hr for the adjacent grassed slope CWB, and 16.7 mm/hr for another grassed slope CYB. The tree-covered slopes TWA and TWB have an average Ø-index of 15.2 and 14.1 mm/hr respectively. Low values were found for the hydroseeded grass slope CYA, 9.9 mm/hr, and the only grass-covered volcanic soil fill slope KOH, 11.7 mm/hr.

For comparison purposes, all of the Ø-index values have been plotted against rainfall duration in Figure 24, in the same way as in the Geotechnical Manual for Slopes (GCO, 1984), see also Figure 5(b). The upper limit for natural catchments given in the Manual is also shown in Figure 24. The data for man-made slopes in this study do not show the trend of decrease with longer duration implied by the upper limit curve. They appear to remain constant at all durations. An upper limit of 40 mm/hr will cover all but two of the data points. It should be noted that 43 data points were used previously, but 287 were used in this study.

The Ø-index analysis discussed above assumes a sharp cut-off from no runoff to full runoff above the Ø-index value. A modified approach was attempted assuming a more gradual change. An initial abstraction was allowed and some proportions of rainfall below a critical intensity were produced as runoff. All rainfall above the critical intensity will be runoff in the same way as in the Ø-index method. The mathematical techniques are provided in Appendix B.6. This modified method allowed an estimation of initial abstraction to be made.

The results from this analysis are given in Table 7, which shows critical intensity ($i_c$), the runoff coefficient for rainfall below the critical intensity (R ), initial abstraction (I), and the correlation coefficient of the equation from which these values were derived. From the definitions, generally the estimated critical intensity is higher than the ø-index, and the R value is less than the actual runoff coefficient. However the relative values between slopes for these parameters show similar characteristics, compare Tables 6 and 7. The estimated initial abstraction values vary from 0.5 mm for the chunammed slope CWA to 14.6 mm for grassed slope CYB. It must be stressed, however, that these are values derived from mathematical correlation on the basis of certain assumptions, and may not represent actual physical quantities.

The average ø-index values in Table 6 and the critical intensities in Table 7 should be compared with the field permeabilities of 6.4 to 55 mm/hr stated in Section 3.1.

## 4.3 Multiple Regression Analysis

Multiple regression analysis was carried out to identify the degrees of correlation between runoff and rainfall parameters, namely rainfall amount, duration, maximum intensity and antecedent rainfall. The standard SPSS package (Nie et al, 1975; Hull and Nie, 1981; and CHASE study - GCO, 1982b) was used for the analysis. The slope TWA was excluded because only five events were recorded there.

At first, one-to-one correlations between runoff and each of the rainfall parameters were investigated for all six slopes. The results are given in Table 8. The best correlation is with the rainfall amount for all slopes. The correlation coefficients varied from 0.985 for the chunammed slope CWA to 0.851 for the grassed slope CWB. There are very poor correlations with the antecedent rainfall; the highest correlation coefficient is only 0.596 for the tree-covered slope TWB.

Further correlation analyses for two, three and four variables were also carried out. These were done for all combinations of the parameters. The sets which gave the highest correlation coefficients are shown in Table 9. This table also provides the relevant multi-variable regression equations. With more variables added to the equations, there were some improvements to the correlation coefficients. The antecedent rainfall appeared to be the best second parameter for the chunammed slope CWA and the tree-covered slope TWB, but the improvements to the correlation coefficients were small.

The equations provided in Table 9 may be used to estimate the runoff, but the user should be cautioned that these are linear correlations without consideration of the actual physical meaning of the equations.

## 4.4 Rainfall-Runoff Relationship

The correlation analysis confirmed that the runoff is almost entirely dependent on the rainfall amount. Additional parameters give only a slight improvement to the relationship. Therefore the rainfall-runoff relationship discussed in Section 2.2.3 may provide a simple and sufficiently accurate method for the estimation of runoff.

The rainfall-runoff relations for the data obtained in this study are shown in Figures 25 to 28 for all of the slopes. The runoff coefficients at different rainfall amounts are also shown in these figures. They show initial losses of 10 to 40 mm except for the chunammed slope CWA. The runoff coefficients in this range are relatively small and scattered. They tend towards a more uniform value at higher rainfall. The average runoff coefficients for rainfall greater than 50 mm are a good indicator of the relative imperviousness of the slopes, see Table 6. They vary from a maximum of 0.93 for the chunammed slope CWA to a minimum of 0.27 for grassed slope CWB. The second highest value, 0.66, is for the volcanic soil fill slope KOH.

In Figures 25 to 28, an envelope was drawn to contain most of the data points for each slope. Instead of using envelopes of arbitrary shape, the well-established SCS curves (Section 2.2.3 and Figure 7) were used for this purpose. Two SCS curves defined the boundary for each slope with the aim of containing 90% of all data. The ranges of SCS curve numbers are provided in Table 6 for these slopes. These envelopes enabled direct comparison of the runoff characteristics of different slopes.

Figure 29 summarises and compares these envelopes from all the slopes except TWA. These curves cover the range of CN (curve number) values from 55 to 100. The data from the chunammed slope CWA are within the CN values 95 to 100, and those for the two grassed slopes CWB and CYB are within the low CN values 55 to 85. Although the surface covers of the other three slopes are different, their runoff responses are similar and could be lumped into the range of CN values between 80 to 100. A simple subtraction of runoff from the rainfall gives potential infiltration, which is also shown in Figure 29. This is the maximum infiltration that may occur in a rainfall event.

## 4.5 Discussion

Three different approaches have been used in the analysis of runoff, namely $\phi$-index, multiple regression and direct rainfall-runoff relationship. However, they give a similar prediction of runoff response, and any of the methods could be used in practice. The choice may depend on the application and the available rainfall data. The linear regression equations and the parameters derived from them have been obtained from mathematical correlation analysis and may not represent actual physical processes and quantities. They provide useful indications of the rainfall-runoff relations, but must be used with caution.

The simple relations provided in Section 4.4 can probably be used directly in slope design and analysis with sufficient accuracy for the purpose. Figure 29 is a simple chart for the estimation of runoff at various rainfall amounts and for different surface covers and soil types. The curves include important characteristics of runoff processes, and have been established on the basis of extensive overseas experience (SCS, 1972; Overton & Meadows, 1976; Hjelmfelt, 1980b), as well as the field data obtained in this study.

In using these relations, it is prudent to adopt a high limit of runoff for surface drainage design, and a high limit of infiltration (corresponding to a low limit of runoff) for stability analysis and design of slopes.

Runoff characteristics are dependent on many factors, including the density and species of vegetation cover. The data obtained in this study indicate that vegetation density is a significant factor. The effects of different vegetation species are not as clear. They are masked by the influences of more significant factors such as the vegetation density and soil type.

Slope angle could also affect the generation of runoff, particularly when it is less than 20° (Nassif & Wilson, 1975). The data set obtained in this study does not permit detailed interpretation of this factor, but it is thought to be secondary in comparison with other factors. All of the slopes studied here have slope angles greater than 28°.

This study has examined rainstorm runoff and infiltration directly on the surface of man-made slopes. There are some situations, however, in which significant changes in groundwater conditions in a man-made slope are caused by infiltration in the area above the slope (Anderson, 1983).

This report covers seven slopes, and these cannot be claimed to represent all commonly encountered surface covers and soil types for slopes in Hong Kong. However, the results should be most useful for slopes with similar characteristics to those reported here. It is also considered that the data for the grassed slopes CWB and CYB provide a lower limit for runoff from man-made grassed slopes. It is noted that the runoff characteristics of these slopes are similar to the natural catchments reported by Government of Hong Kong (1968) and GCO (1982a).

The tree-covered slope TWB and hydroseeded slope CYA appear to provide substantial improvement in generating runoff over turfed slopes. However, it should be noted that TWB was monitored for only one year (1985), and CYA was covered with a layer of protective material (Bemnet) in the early stage of hydroseeding (1984). For the latter case, all the very high runoff was generated in early 1984; presumably, the protective layer decayed some time later.

It has been demonstrated here that chunam cover is very much more effective in generating runoff, and hence limiting infiltration, than vegetation cover. However, vegetation may contribute to greater stability through the contribution of the root system to the soil mass strength (Greenway et al, 1984). Extensive tree cover to slopes, such as in TWB, may be able to provide both a reduction in infiltration and additional strength from roots. However, detailed evaluation of the right balance between the beneficial and detrimental effects of vegetation covers would be better considered on an individual slope basis. The effectiveness of vegetation cover may also be better evaluated if accurate and representative values of field surface detention and root zone permeability were known (Anderson, 1983). However these parameters, particularly the first, cannot be estimated with any certainty, see the review in Section 2.1.

It should be emphasized that the data were gathered for a period of only one to two years. Most of the slopes were also newly constructed. They may provide runoff responses which are different from those of long-established slopes with more mature vegetation. Since heavy rainstorms are infrequent, in this study there were only two to six rainstorms having rainfall greater than 100 mm at each slope, with a maximum of 276 mm. Heavy rainstorms are much more important to slope stability than more frequent light rainstorms (Brand et al 1984). It is also desirable to obtain additional data on other slopes, such as weathered volcanic cut slopes and slopes with covers of other vegetation types. Therefore, continuation of monitoring at the established sites and establishment of new sites are considered necessary to confirm the relations established in this report.

## 5. CONCLUSIONS

(a) This report has compiled rainfall-runoff data from seven man-made slopes during the two-year period 1984-85. The runoff from all slopes has been found to be largely dependent on the rainfall amount, while other parameters such as antecedent rainfall and duration contribute small secondary effects.

(b) There are initial losses at low rainfall of about 10 to 40 mm, when almost no runoff is produced, and a gradual increase in runoff at higher rainfall. The initial loss is interpreted to be a small surface abstraction plus a large initial infiltration. The relatively small losses at high rainfall could be infiltration at the limiting rate.

(c) Chunam cover is effective in preventing infiltration, in contrast to grass covers, which could allow infiltration up to a maximum of 70% of rainfall. Hydroseeding and closely-spaced tree cover could provide improvement over turfing in preventing infiltration.

(d) Not surprisingly, the compacted volcanic soil fill slope appeared to allow less infiltration than the weathered granite cut slopes. These findings are summarised in Figure 29.

## 6. RECOMMENDATIONS

(a) The relationships established on the basis of the initial field data contained herein, particularly Figure 29, may be used in the estimation of runoff and infiltration, with the limitations discussed in Section 4.5.

(b) These relationships should be confirmed and developed further by the continuation of field monitoring of rainstorm runoff at established sites, and by the establishment of new sites.

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# LIST OF TABLES

Table 1 - Runoff Regression Equations from the Previous Study by Hsu et al (1983)

| No. of Data Sets | Chunammed Slope | Grassed Slope |
|---|---|---|
| 52 | Q = 0.8392 P - 0.0191 t - 1.552<br>(R = 0.9672) | Q = 0.3514 P - 0.0093 t - 1.247<br>(R = 0.9486) |

Legend :

| | |
|---|---|
| Q | Runoff amount in mm |
| P | Rainfall in mm |
| t | Duration of rainfall in minutes |
| R | Multiple regression coefficient |

Table 2 - Characteristics of the Slopes and the Instrumentation

| Code | Slope | Plan Area ($m^2$) | Slope Angle (deg) | Soil Type | Surface Covering / Vegetation | Raingauge Used | Distance from Raingauge (km) | Weir Angle (deg) |
|---|---|---|---|---|---|---|---|---|
| CWA | Clear Water Bay Rd A | 280 | 60 | Highly / completely decomposed granite | Chunam | N08 | 0 | 17 |
| CWB | Clear Water Bay Rd B | 260 | 45 | Highly / completely decomposed granite | Grass with some trees | N08 | 0.20 | 17 |
| KOH | Kohima Barracks | 710 | 30 | Volcanic fill | Grass with some trees | N16 | 0 | 65 |
| CYA | Chuk Yuen A | 410 | 35 | Highly decomposed granite | Hydroseeded grass | K02 * | 0.95 (0.21) | 24 |
| CYB | Chuk Yuen B | 410 | 35 | Highly decomposed granite | Turfed grass | K02 * | 0.99 (0.24) | 24 |
| TWA | Tsuen Wan A | 530 | 30 | Highly / completely decomposed granite | Grass with dense trees | N03 * | 1.21 (0.19) | 22 |
| TWB | Tsuen Wan B | 330 | 28 | Moderately / highly decomposed granite | Grass with dense trees | N03 * | 0.97 (0.03) | 22 |

Legend

* Autographic raingauges were used to supplement the GCO automatic raingauges.

Table 3 - Observed Data on the Conditions of Surface Covers at the Seven Slopes

| Slope | Well-developed Trees More Than 2m High | | Shrubs & Immature Trees Less Than 2m High | | Estimated Density of Grass per $m^2$ |
|---|---|---|---|---|---|
| | No. | Average Spacing (m) | No. | Average Spacing (m) | |
| CWB | 7 | 6.1 | 21 | 3.5 | 600 - 800 |
| TWA | 70 | 2.8 | 20 | 5.0 | 300 - 1100 |
| TWB | 72 | 2.1 | 21 | 4.0 | 500 - 650 |
| CYA | - | - | 15 | - * | 500 - 700 |
| CYB | - | - | 25 | - * | 400 - 500 |
| KOH | - | - | 68 | 6.0 | 1000 - 1900 |
| CWA (Chunam) | There are cracks generally less than 0.5mm wide with a few cracks up to 4mm wide. The total crack length is about 6000mm/$m^2$. This is classed as poor condition on the scale of bad - poor - average used by Anderson (1983) | | | | |

Legend :

* Shrubs are concentrated in a few groups, not evenly distributed.

Note : (1) Data based on field observation and measurements on 9.7.1986.
(2) Photographs of the slope covers are shown in Plates 1 to 7.
(3) Other details of the slopes are given in Tables 2 and 4.

**Table 4 - Species of Vegetation on the Slopes**

| Slope | Vegetation | |
|---|---|---|
| | Common Name | Scientific Name |
| CWB | Golden Fern<br>Weeping Love<br>Oriental Blechnum<br><br>Slash Pine<br>Horsetail Tree | Pityrogramma tartarea<br>Eragrostis curvula<br>Blechnum orientale<br><br>Pinus elliottii<br>Casuarina sp. |
| TWA | -<br>Bur Grass<br><br>Yellow Oleander (60 %)*<br>Elephant's Ear (30 %)<br>Lebbek Tree (10 %) | Achyranthes sp.<br>Cenchrus echinatus L.<br><br>Thevetia peruviana<br>Macaranga tanarius<br>Albizia lebbek |
| TWB | Hilo Grass<br>Beggar Weed<br>Hairy Bur-Marigold<br><br>Acacia (90 %)<br>Horsetail Tree (10 %) | Paspalum sp.<br>Desmodium tortuosum<br>Bidens pilosa<br><br>Acacia confusa<br>Casuarina equisetifolia |
| CYA | Bermuda<br>Bahia<br>Weeping Love | Cynodon dactylon<br>Paspalum notatum<br>Eragrostis curvula |
| CYB | Panic Grass<br>India Duck-beak<br>Hilo Grass | Panicum sp.<br>Ischaemum indicum<br>Paspalum conjugatum |
| KOH | Panic Grass<br>India Duck-beak<br>Slash Pine | Panicum sp.<br>Ischaemum indicum<br>Pinus elliottii |

Legend :

* Percentages relate to relative numbers of trees only.

**Table 5 - Weir Constants Used in the Calculation of Runoff**

| Slope | Weir Angle | K* | n* | Date of Calibration |
|---|---|---|---|---|
| CWA<br>CWB | 17° | 0.141<br>(2.82)* | 2.20<br>(4.00)* | 28.5.86 |
| TWA<br>TWB | 22° | 0.190 | 2.20 | 6.6.86 |
| CYA<br>CYB | 24° | 0.211 | 2.20 | 21.5.86 |
| KOH | 65° | 0.536 | 2.20 | 26.6.86 |

Legend :

* Values from calibration of wiers ; $Q = Kh^n$.

* Compound wier with rectangular wier on top of V-notch ; constants in brackets were used when h was greater than 0.190 m.

**Table 6 - Average Ø-index Values, Runoff Coefficients and Ranges of SCS Curve Numbers for the Seven Slopes**

| Slope | Average Φ - index (mm/hr) | Average Runoff Coefficient * | SCS Curve Numbers * |
|---|---|---|---|
| CWA | 1.8 | 0.93 | 100 - 95 |
| CWB | 16.9 | 0.27 | 85 - 55 |
| TWA | 15.2 | - | - |
| TWB | 14.1 | 0.56 | 95 - 80 |
| CYA | 9.9 | 0.57 | 100 - 80 |
| CYB | 16.7 | 0.40 | 85 - 60 |
| KOH | 11.7 | 0.66 | 100 - 80 |

Legend :

* Average for the events with rainfall greater than 50 mm.

* See Section 2.2.3 and Appendix B.4. The range covers about 90 % of the data for each slope.

Table 7 - Results from the Modified $\phi$-index Analysis

| Slope | ic (mm / hr) | R | I (mm) | N | Correlation Coefficient |
|---|---|---|---|---|---|
| CWA | 17 | 0.78 | 0.5 | 37 | 0.722 |
| TWB | 29 | 0.50 | 13.5 | 13 | 0.940 |
| CYA | 13 | 0.35 | 10.9 | 50 | 0.851 |
| CYB | 37 | 0.42 | 14.6 | 23 | 0.878 |
| KOH | 9 | 0.64 | 14.4 | 40 | 0.436 |

Legend :

- ic Critical intensity
- R Runoff coefficient for rainfall less than ic
- I Initial abstraction
  ( these were estimated from regression equations, the correlation coefficients of which are shown above, see also Section 4.2 and Appendix B.6 ).
- N Number of rainstorms used in the analysis. Those with maximum intensity less than ic were excluded.

Note : Two slopes were not included; CWB gave negative I and TWA did not have sufficient data.

Table 8 - Summary of the Results from Simple Regression Analysis Correlating Runoff with One of the Variables

| Slope * | Correlation Coefficient for Correlation to Runoff | | | | | No. of Data Sets Used |
|---|---|---|---|---|---|---|
| | Rainfall Amount | Duration | Maximum Intensity | Antecedent Rainfall (mm) | | |
| | | | | 5 - day | 15 - day | |
| CWA | 0.985 | 0.588 | 0.681 | 0.041 | 0.130 | 58 |
| CWB | 0.851 | 0.211 | 0.701 | - 0.152 * | - 0.053 | 56 |
| TWB | 0.962 | 0.686 | 0.629 | 0.596 | 0.575 | 20 |
| CYA | 0.952 | 0.444 | 0.830 | - 0.160 | - 0.069 | 54 |
| CYB | 0.946 | 0.374 | 0.803 | - 0.074 | 0.042 | 54 |
| KOH | 0.927 | 0.745 | 0.659 | - 0.021 | - 0.044 | 45 |

Legend :

* For TWA, the number of data sets is not sufficient to produce significant statistical correlations.

* Negative values indicate inverse relationship.

Table 9 - Summary of the Results from Multiple Regression Analysis

| Slope | No. of Variables | Coefficients | | | | | Constant | Multiple Regression Coefficient |
|---|---|---|---|---|---|---|---|---|
| | | a | b | c | d | e | f | |
| CWA | 1 | 0.888 | | | | | 1.38 | 0.985 |
| | 2 | 0.888 | | | 0.017 | | -2.54 | 0.986 |
| | 3 | 0.926 | -0.323 | | 0.023 | | -2.12 | 0.987 |
| | 4 | 0.942 | -0.350 | -0.314 | 0.022 | | -1.52 | 0.987 |
| CWB | 1 | 0.307 | | | | | -2.11 | 0.851 |
| | 2 | 0.405 | -1.111 | | | | 1.62 | 0.926 |
| | 3 | 0.367 | -0.967 | 0.074 | | | -0.41 | 0.930 |
| | 4 | 0.361 | -0.901 | 0.082 | | -0.010 | 0.55 | 0.933 |
| TWB | 1 | 0.557 | | | | | -5.27 | 0.962 |
| | 2 | 0.507 | | | | 0.030 | -8.44 | 0.979 |
| | 3 | 0.499 | 0.103 | | | 0.029 | -8.53 | 0.979 |
| | 4 | 0.480 | 0.163 | 0.045 | 0.043 | | -8.17 | 0.976 |
| CYA | 1 | 0.659 | | | | | -7.00 | 0.952 |
| | 2 | 0.542 | | 0.270 | | | -11.95 | 0.961 |
| | 3 | 0.597 | -0.279 | 0.210 | | | -9.74 | 0.963 |
| | 4 | 0.589 | -0.286 | 0.220 | 0.021 | | -8.15 | 0.964 |
| CYB | 1 | 0.524 | | | | | -8.35 | 0.946 |
| | 2 | 0.565 | -0.448 | | | | -6.44 | 0.954 |
| | 3 | 0.521 | -0.364 | 0.082 | | | -8.29 | 0.955 |
| | 4 | 0.520 | -0.348 | 0.082 | | 0.007 | -9.70 | 0.956 |
| KOH | 1 | 0.786 | | | | | -7.26 | 0.927 |
| | 2 | 0.905 | | -0.369 | | | -0.63 | 0.933 |
| | 3 | 0.949 | | -0.461 | | 0.043 | -6.55 | 0.941 |
| | 4 | 0.887 | 0.411 | -0.413 | | 0.047 | -8.96 | 0.942 |

Note :

(1) The runoff can be estimated from
Runoff (mm) = a · rainfall(mm) + b · duration (hr) + c · max. intensity (mm/hr)
+ d · 5 - day antecedent rainfall (mm)
+ e · 15 - day antecedent rainfall (mm) + f (constant).

(2) For an equation with n variables, all possible combinations of the 3 variables plus one of the antecedent rainfalls were used in the regression analysis, and the set which provided the highest multiple regression coefficient is shown here.

(3) For TWA, the number of data sets is not sufficient to produce significant statistical correlations.

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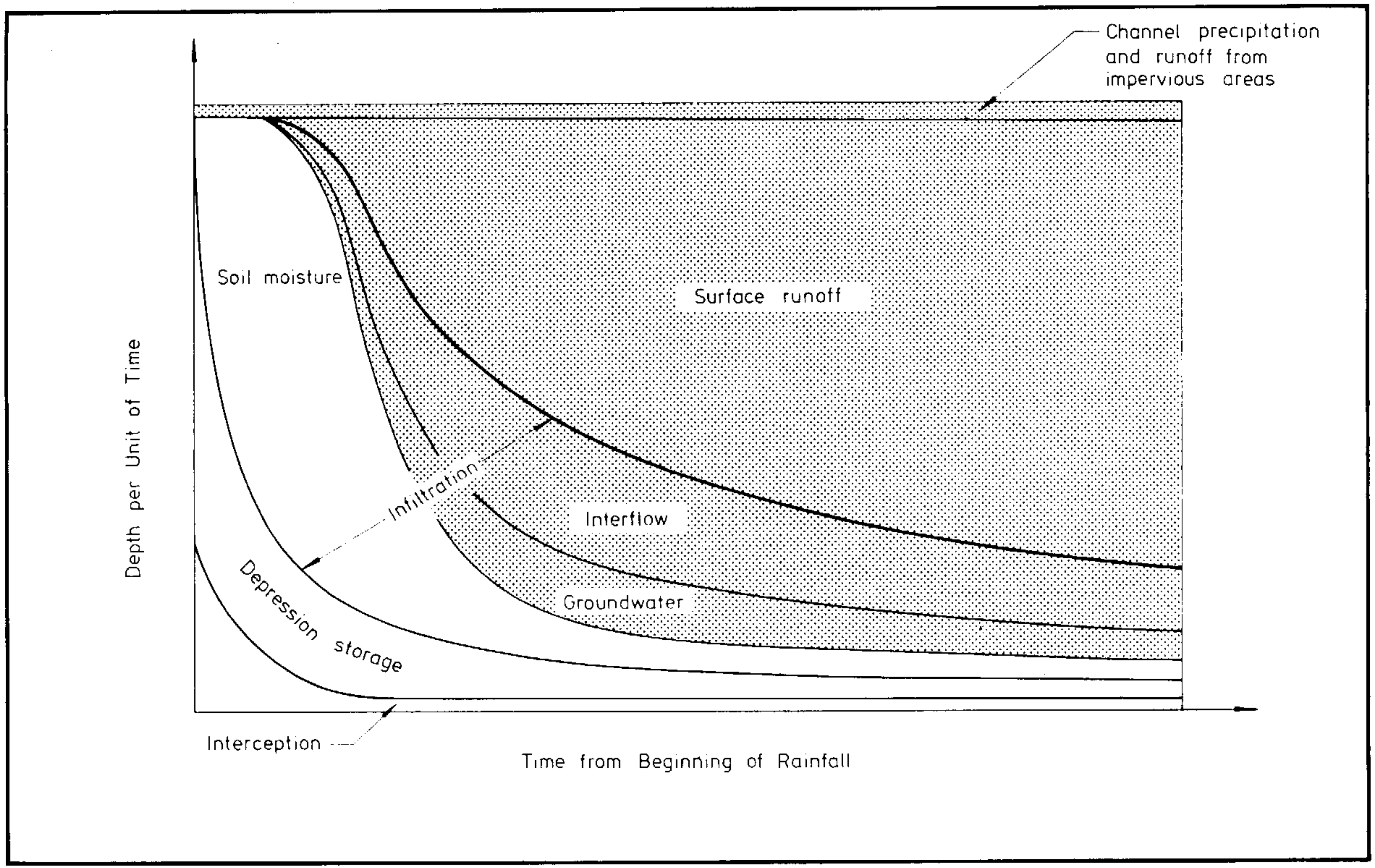



Figure 1 - Schematic Diagram of the Components of Storm Rainfall (after Linsley et al, 1982)

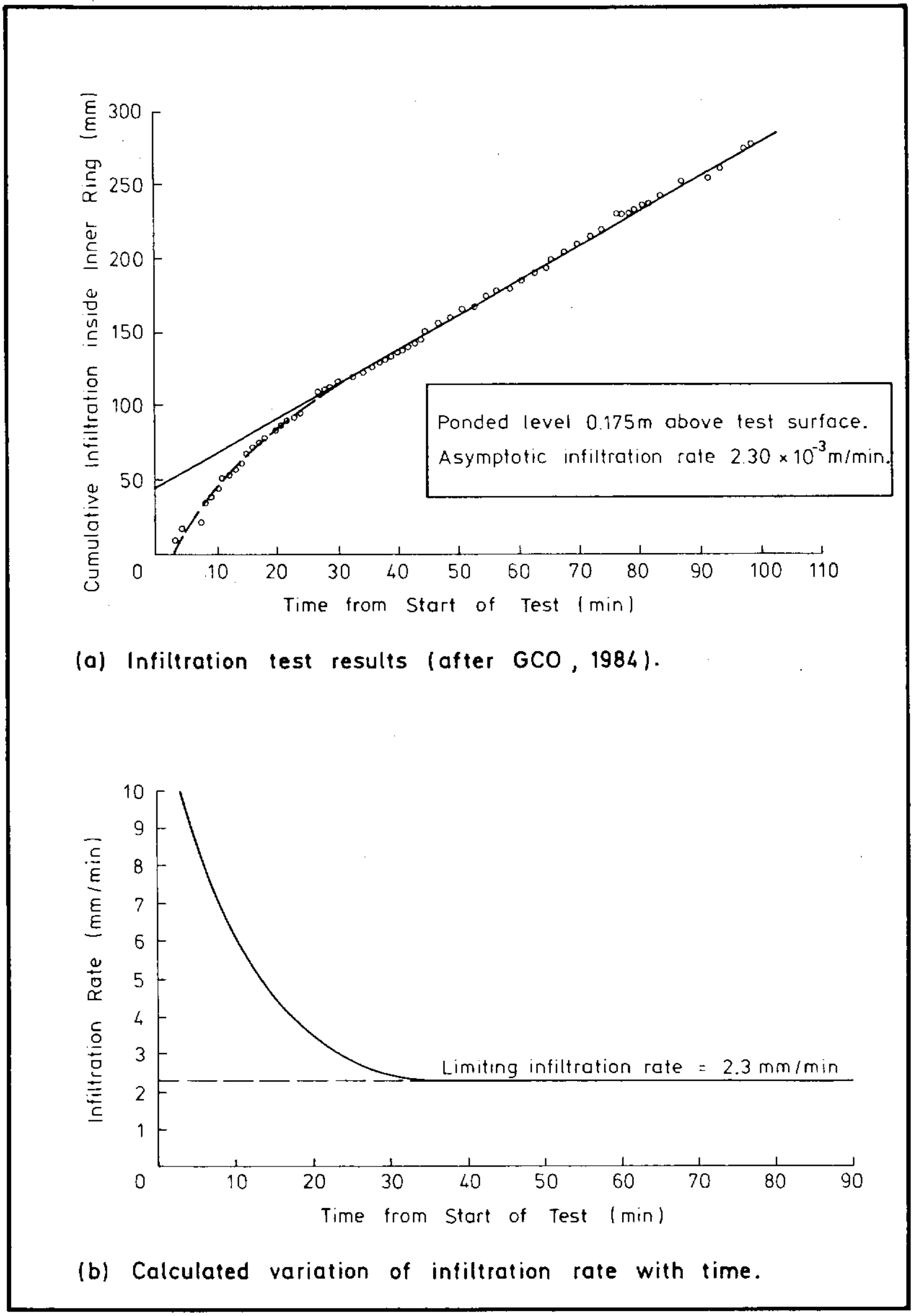
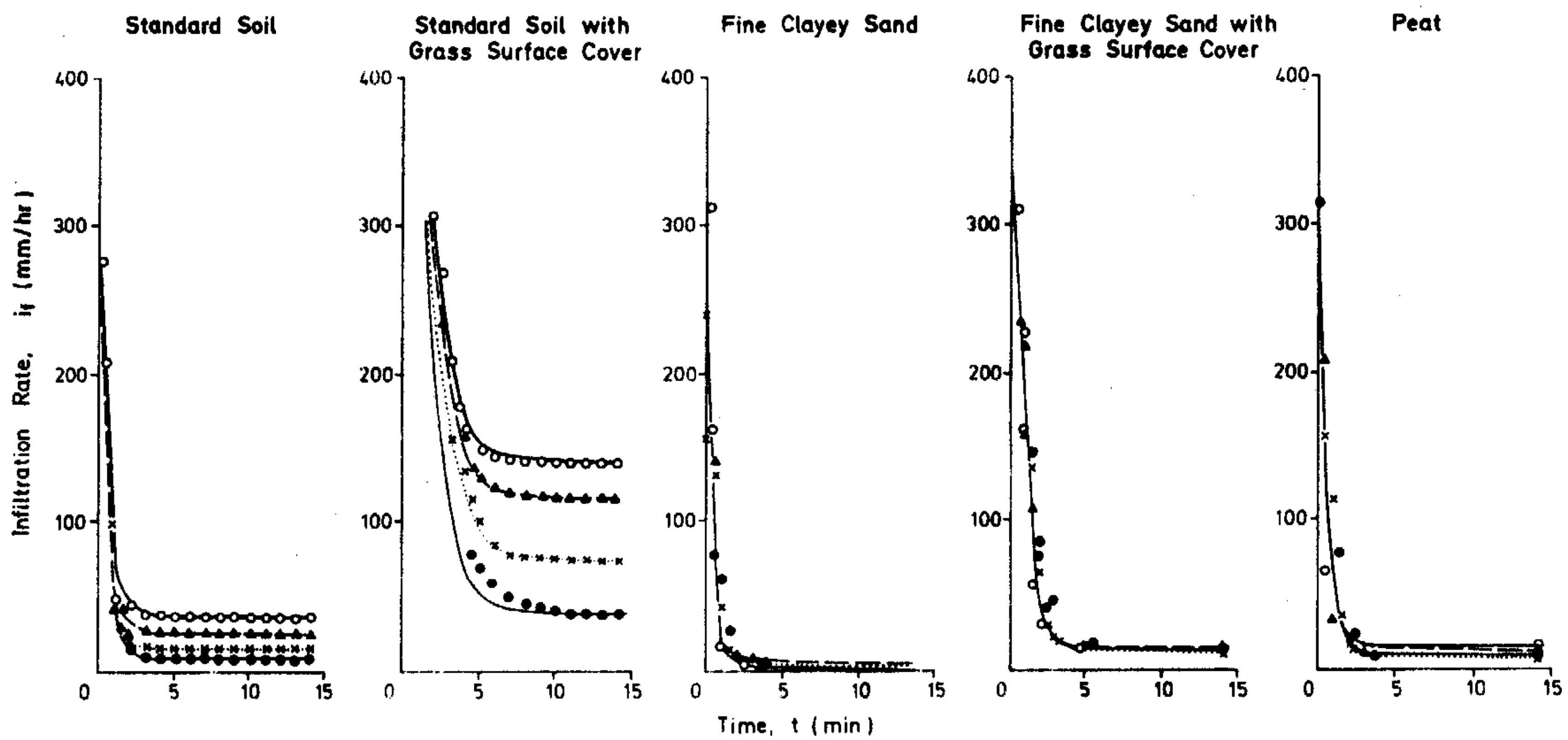



**Figure 2 – Typical Infiltration Test Results in Hong Kong**




Legend :

| Theoretical | Observed | Rain Intensity, $i_p$ | Theoretical | Observed | Rain Intensity, $i_p$ |
|---|---|---|---|---|---|
| ——— (solid) | ○ | 312 mm/hr | ········ (dotted) | × | 156 mm/hr |
| — — — (dashed) | ▲ | 234 mm/hr | ——— (solid) | ● | 76 mm/hr |

Note : The theoretical curve refers to an empirical equation by Horton (1939) in which the decrease in infiltration rate, $i_f$ with time, t is described by an exponential decay curve of the form, $i_{f(t)} = i_{f\infty} + \mu^{-kt}$.

Figure 3 - Laboratory Infiltration Test Results (after Nassif & Wilson, 1975)

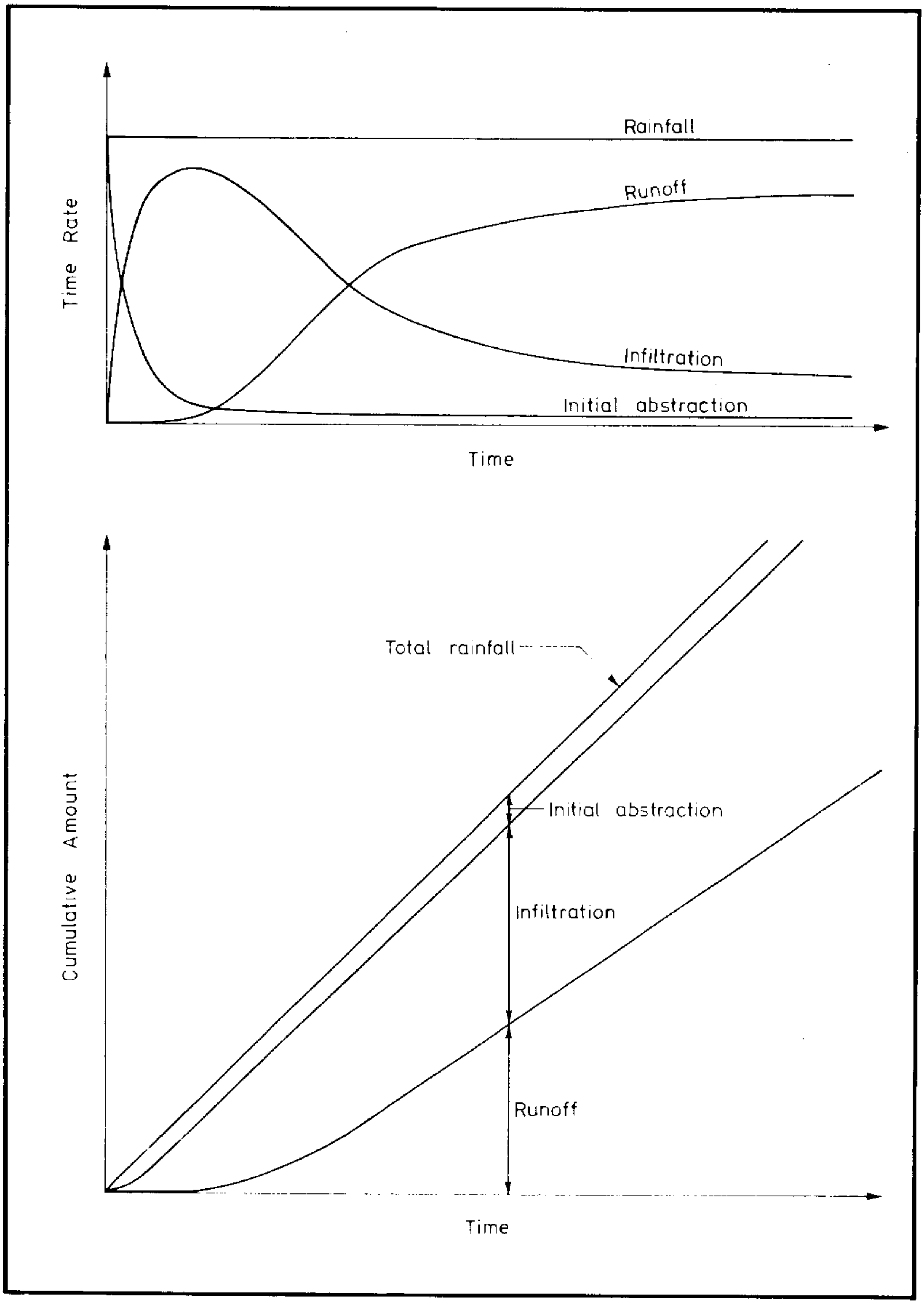



Figure 4 - Time Rate and Cumulative Amount of the Components of Storm Rainfall

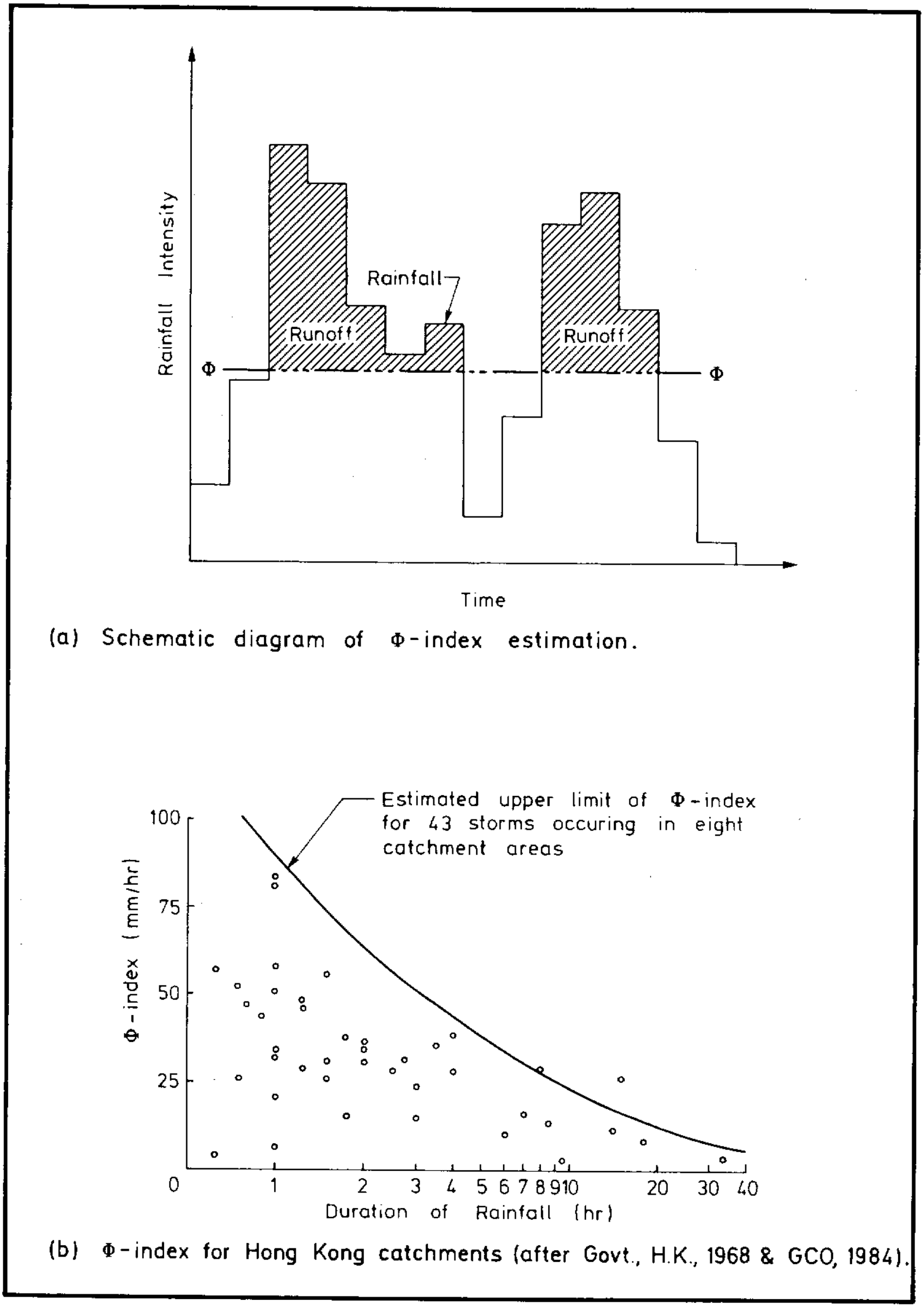
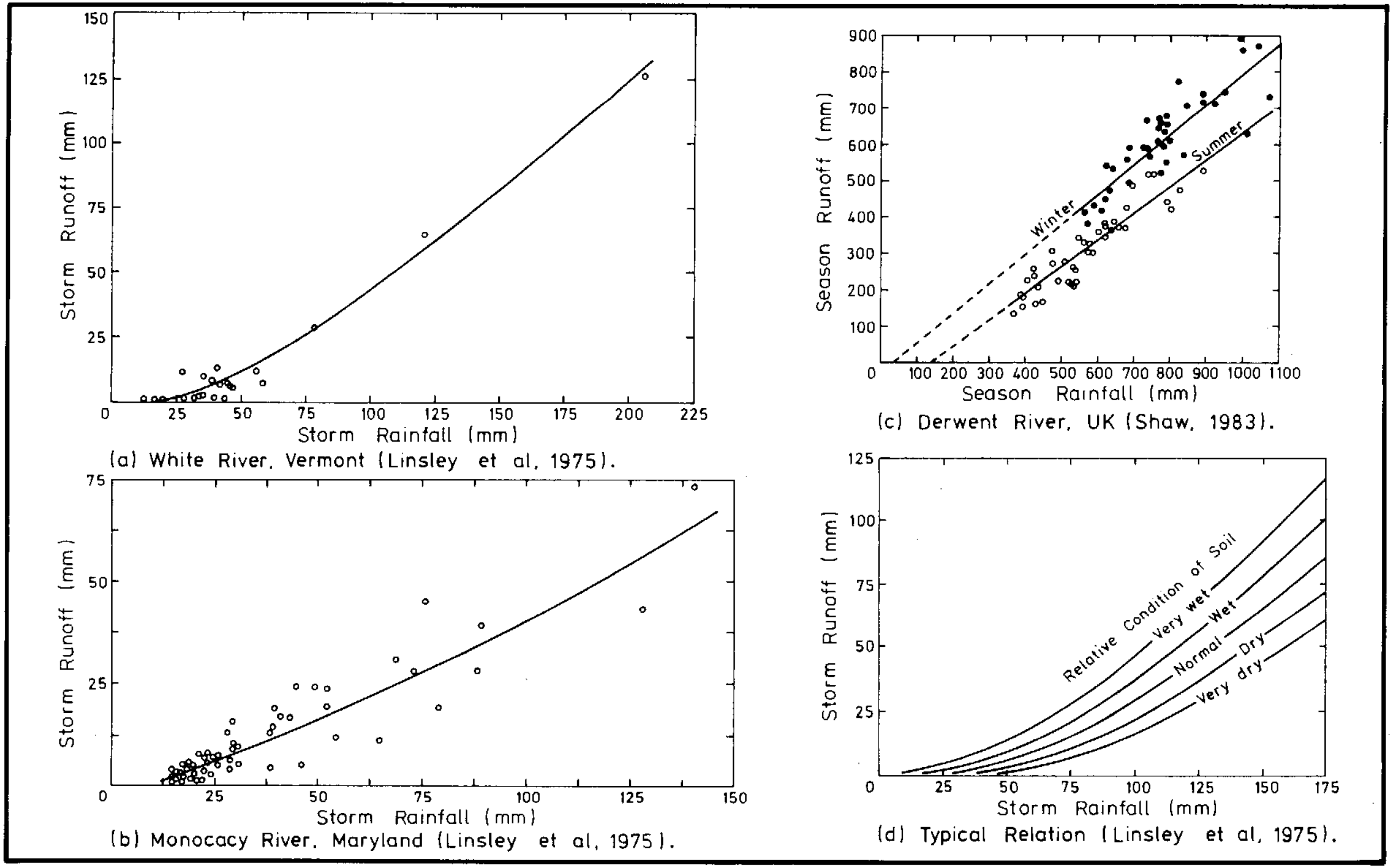



**Figure 5 – Ø-index Estimation and the Values for Hong Kong Natural Catchments**




(a) White River, Vermont (Linsley et al, 1975).

(b) Monocacy River, Maryland (Linsley et al, 1975).

(c) Derwent River, UK (Shaw, 1983).

(d) Typical Relation (Linsley et al, 1975).

**Figure 6 – Case Studies on Rainfall-Runoff Relationships**

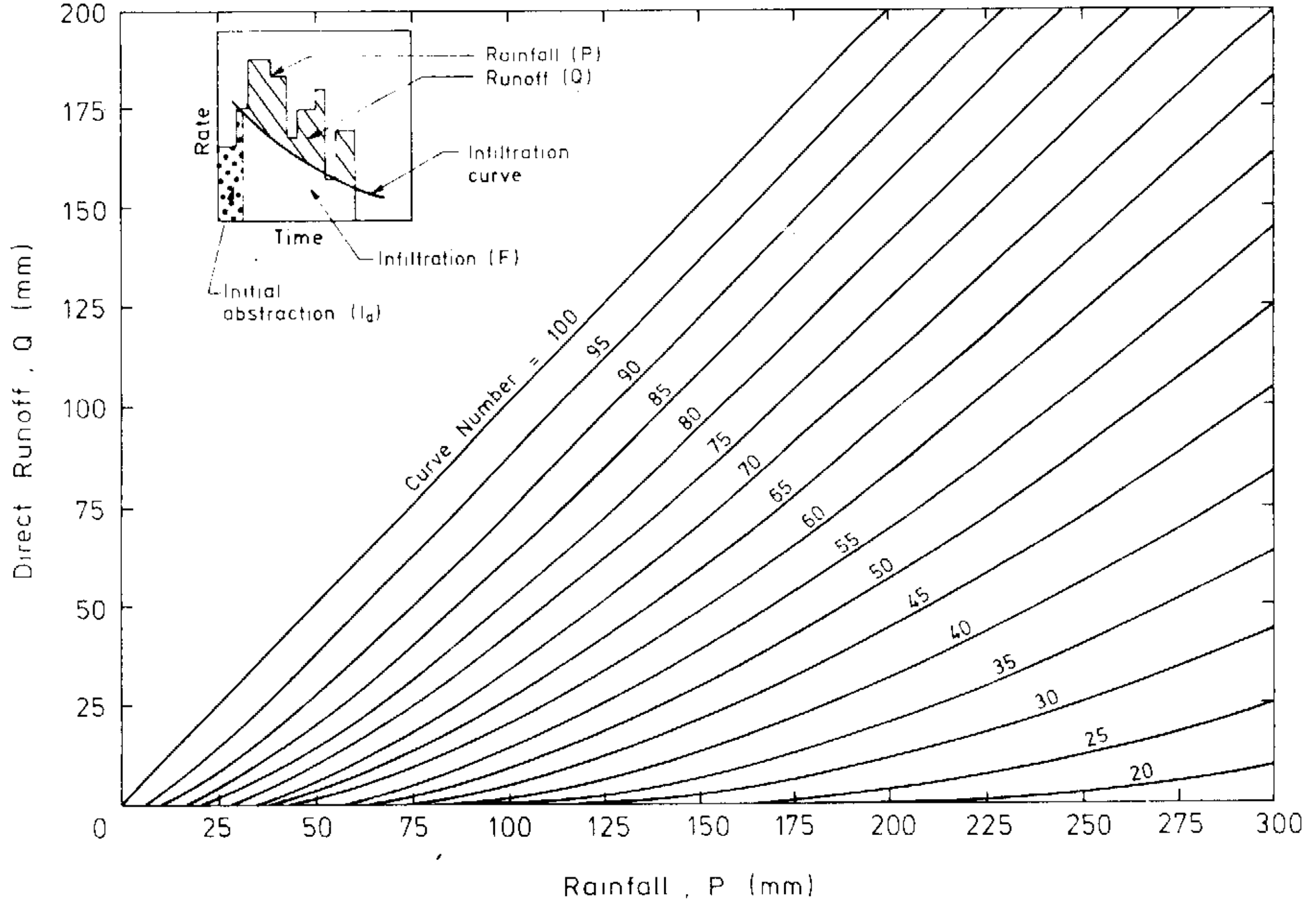



Figure 7 – The US Soil Conservation Service Curve Number Chart for the Estimation of Runoff (after Overton & Meadows, 1976)

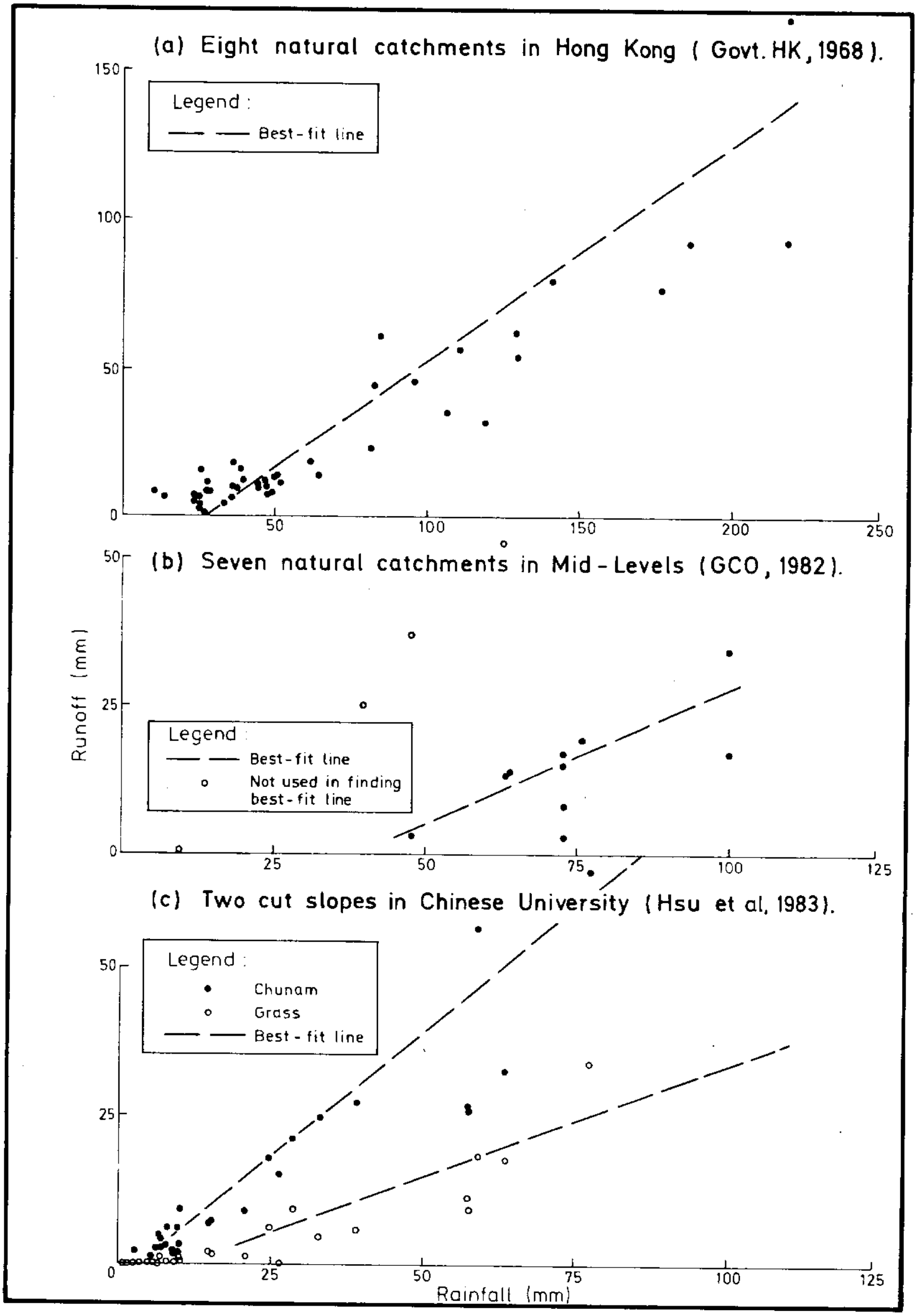



Figure 8 - Summary of the Results from Hong Kong Runoff Studies

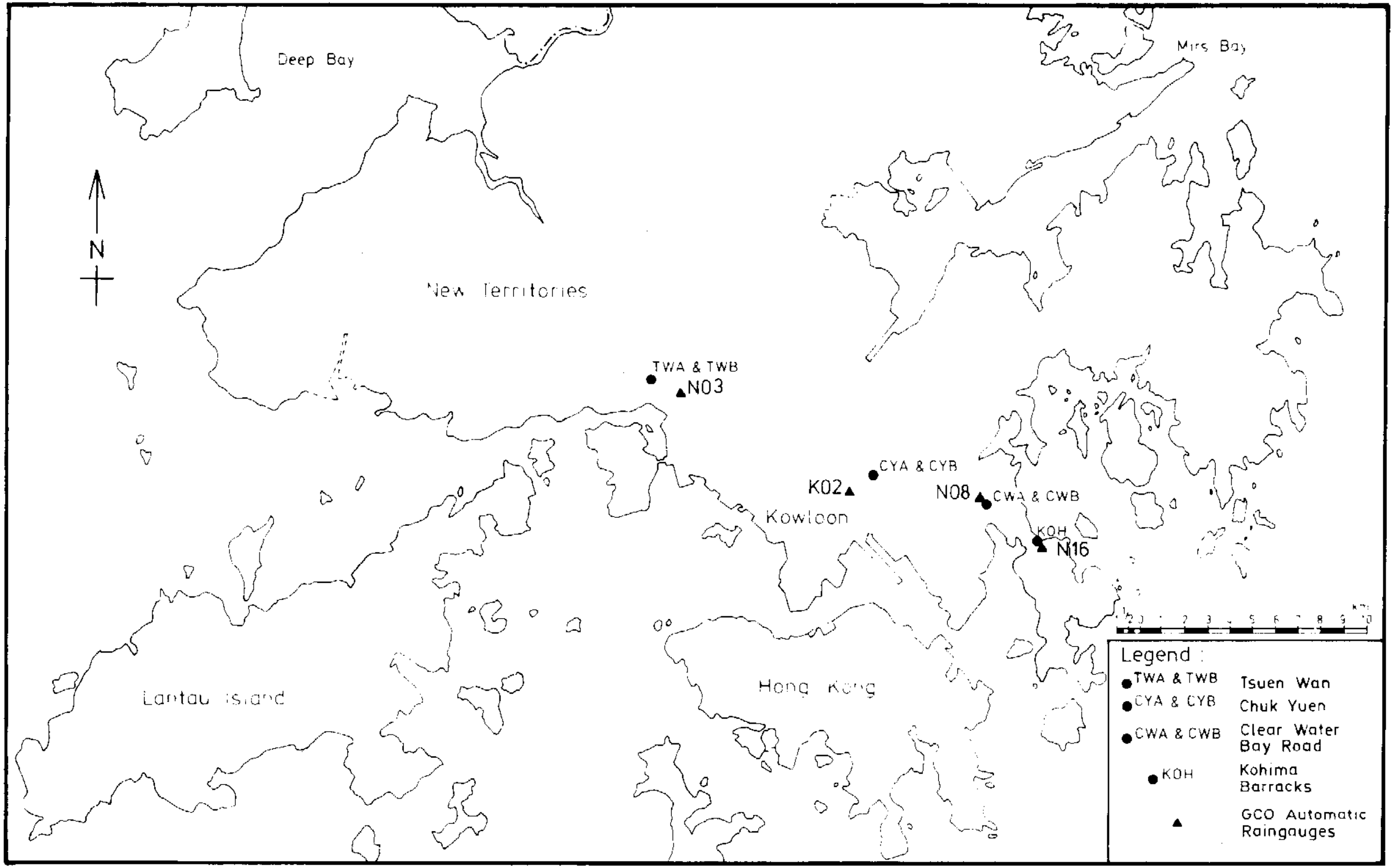



Figure 9 - Location Plan of Slopes and Raingauges

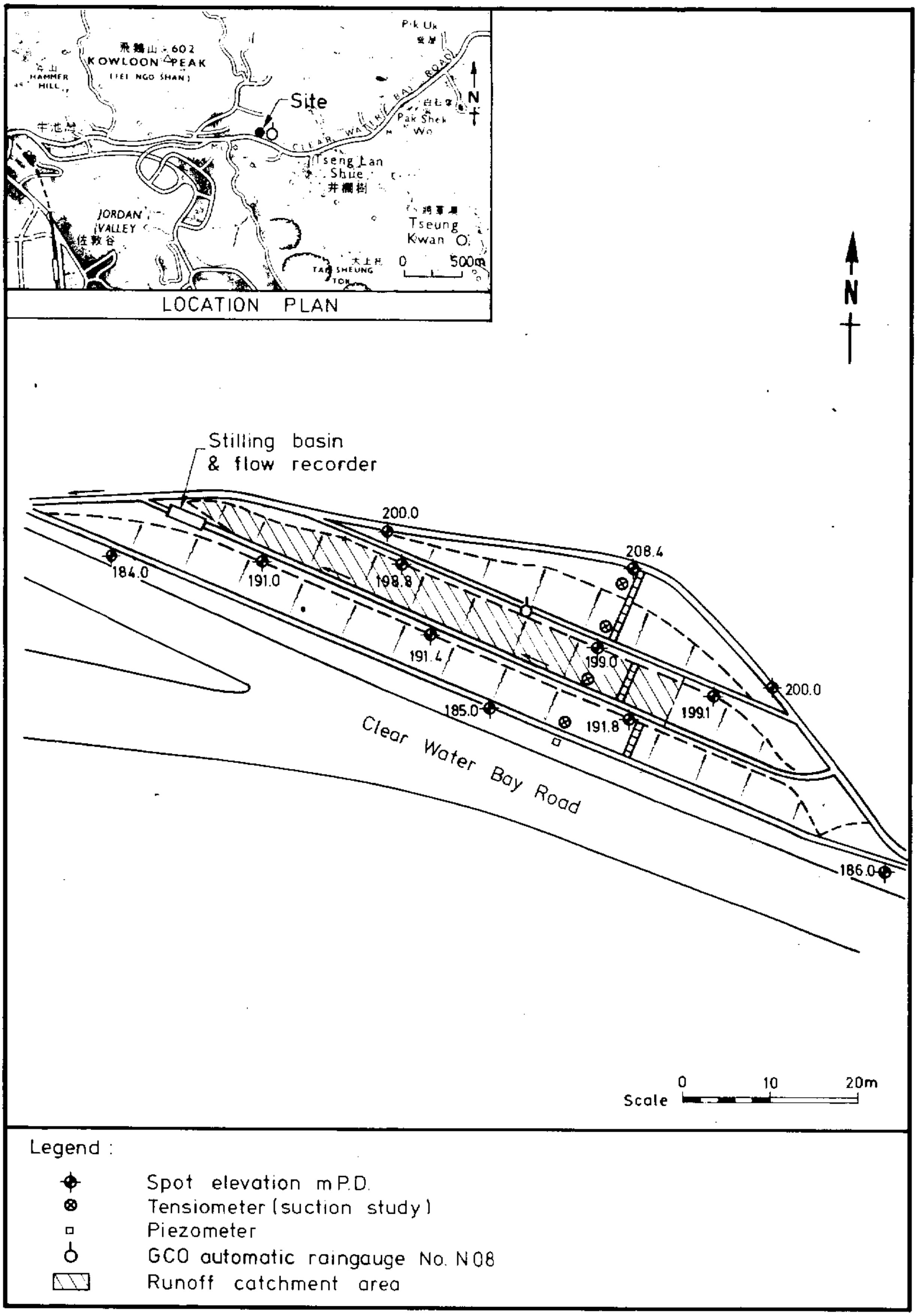



Figure 10 – Site Plan for the Runoff Plot on Clear Water Bay Road Chunammed Slope (CWA)

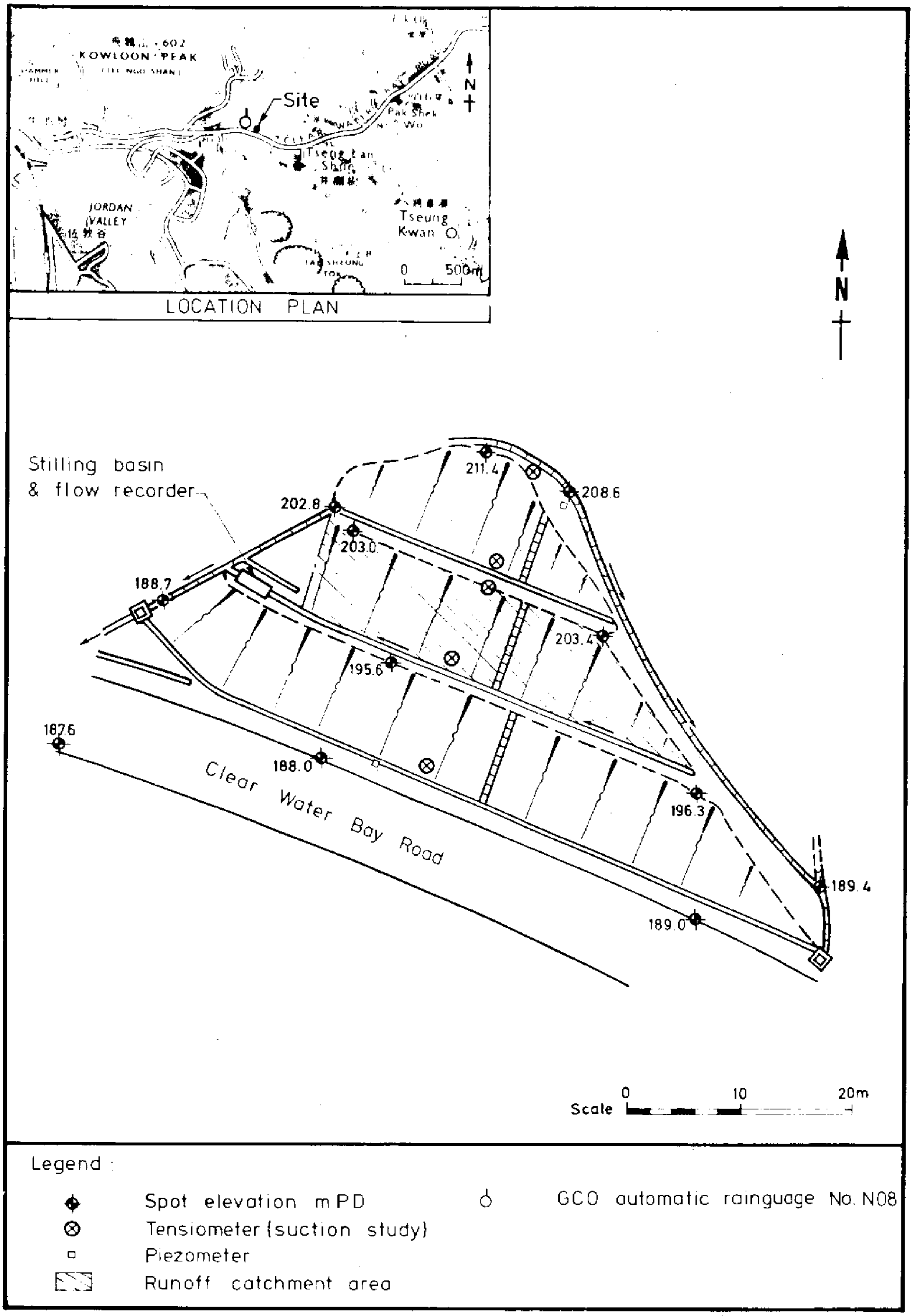



Figure 11 - Site Plan for the Runoff Plot on Clear Water Bay Road Grassed Slope (CWB)

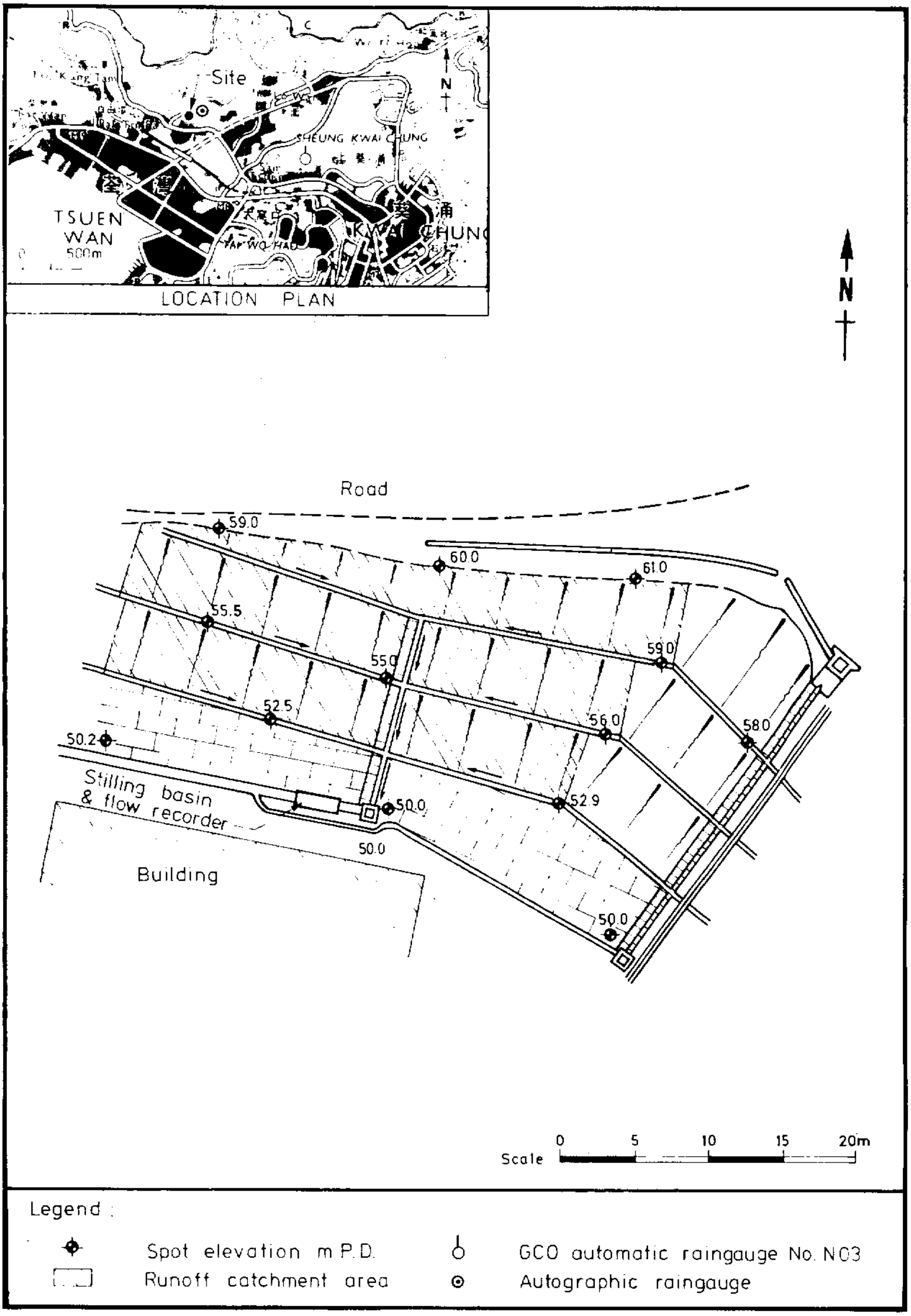



Figure 12 - Site Plan for the Runoff Plot at Tsuen Wan (TWA)

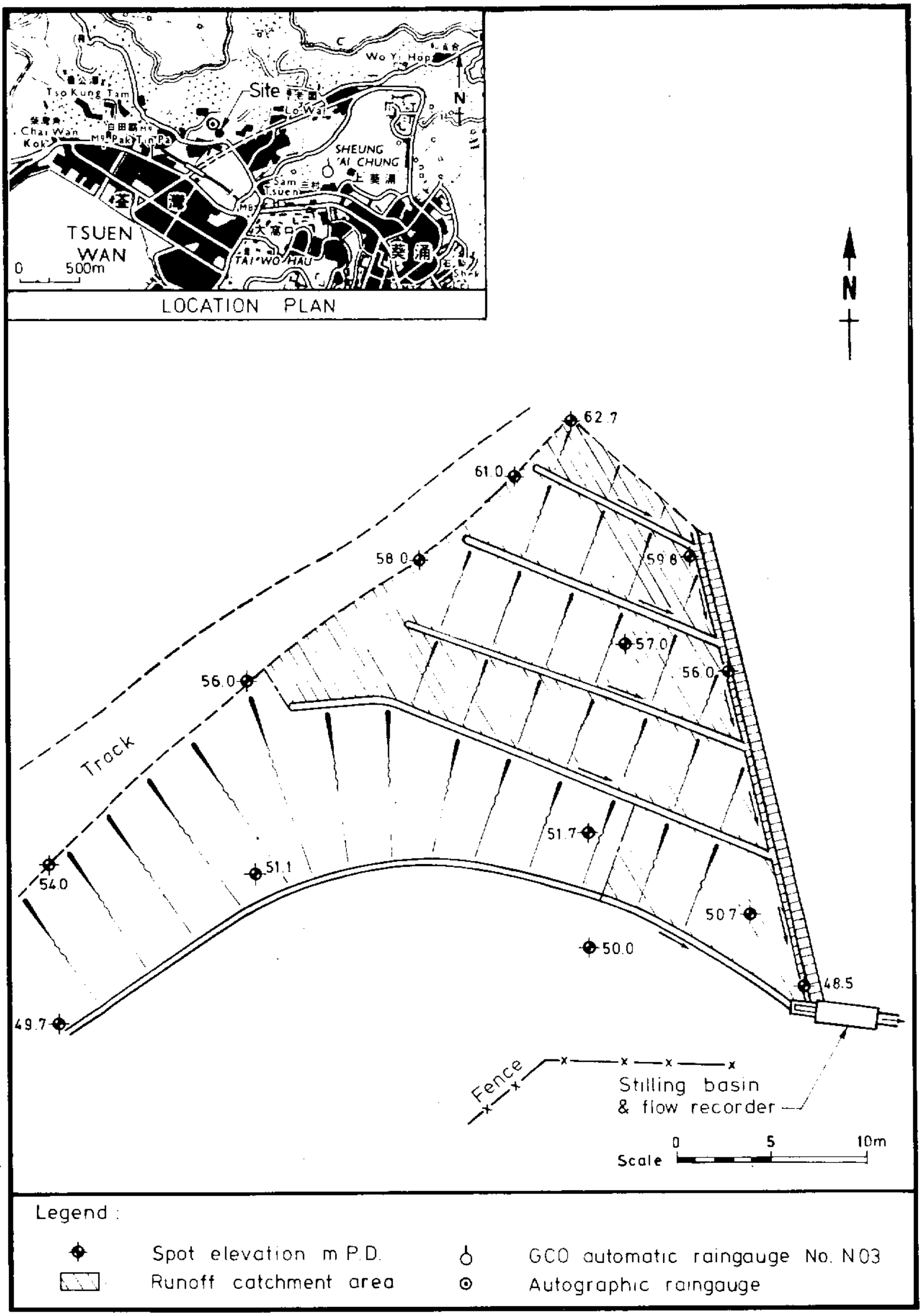



Figure 13 - Site Plan for the Runoff Plot at Tsuen Wan (TWB)

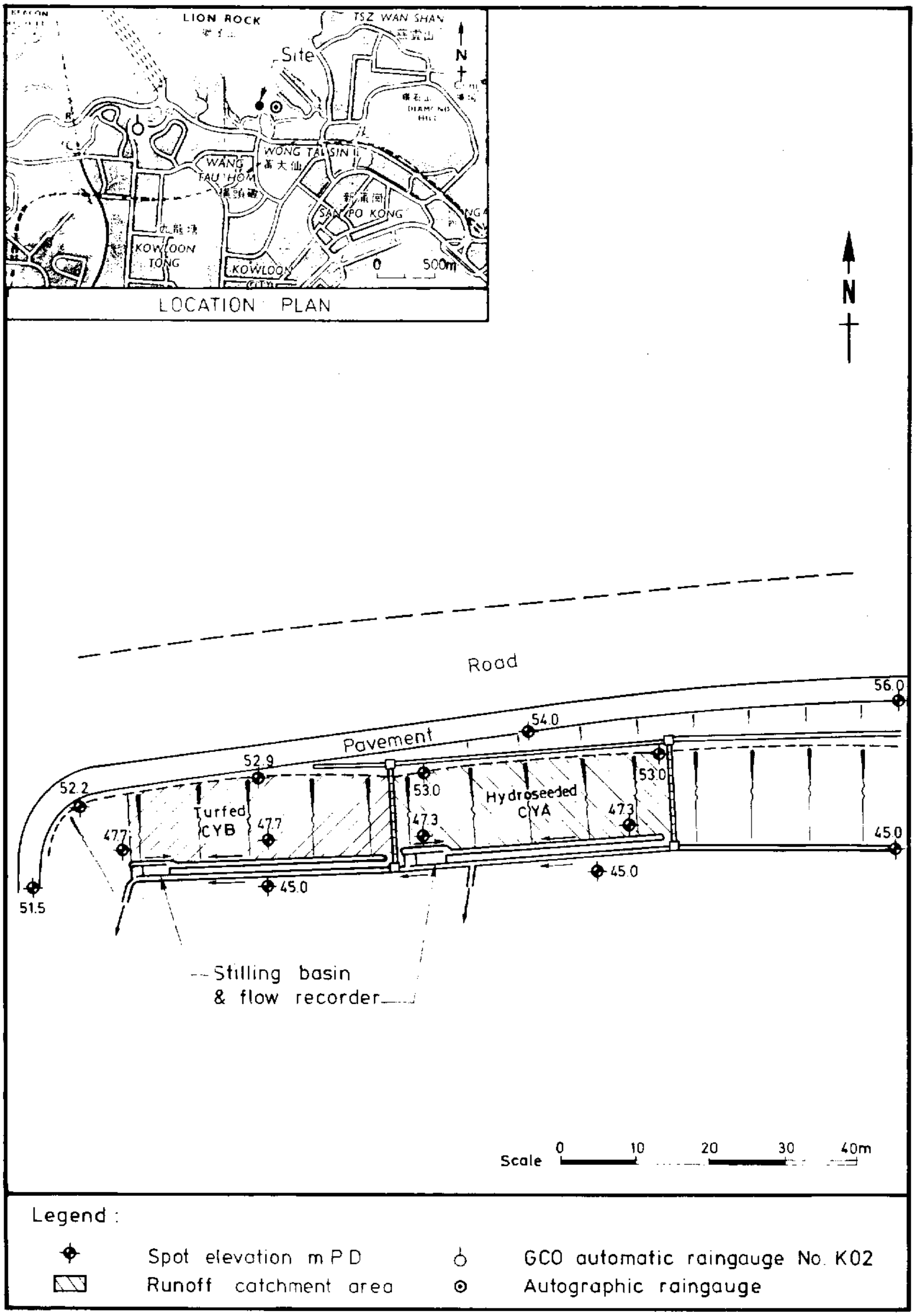



Figure 14 - Site Plan for the Runoff Plots at Chuk Yuen (CYA & CYB)

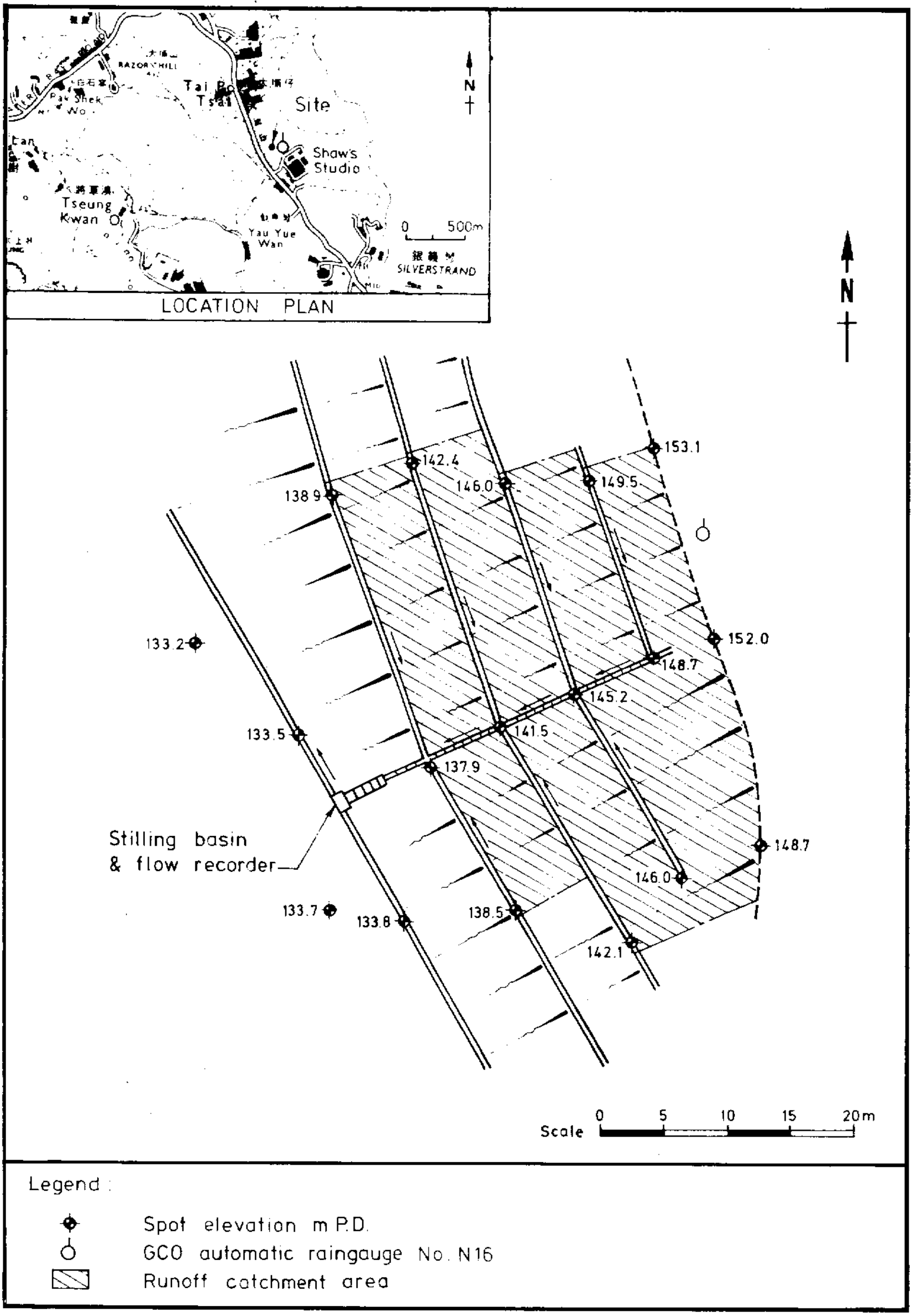



Figure 15 - Site Plan for the Runoff Plot at Kohima Barracks (KOH)

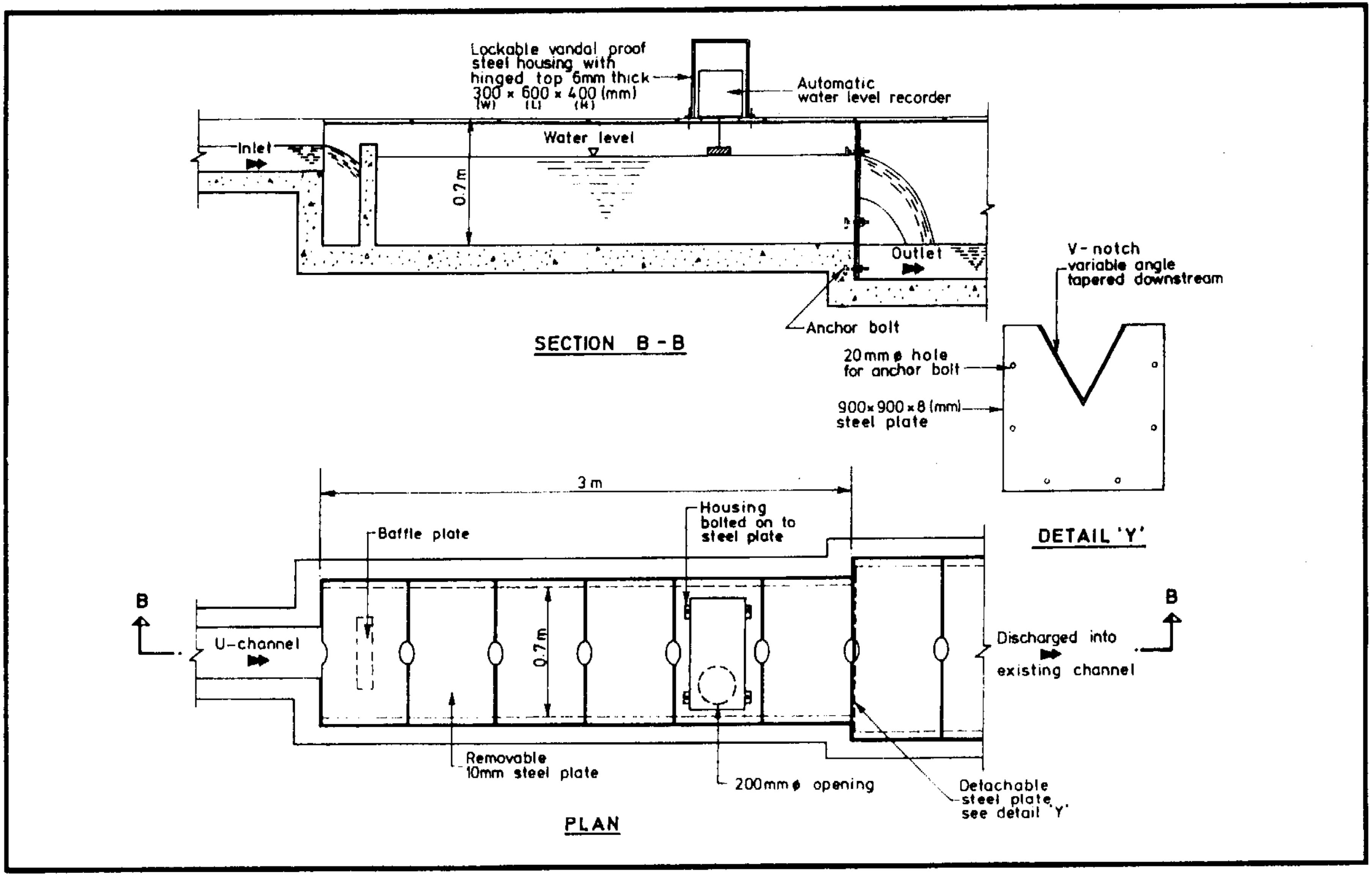



Figure 16 - Details of the Stilling Basin

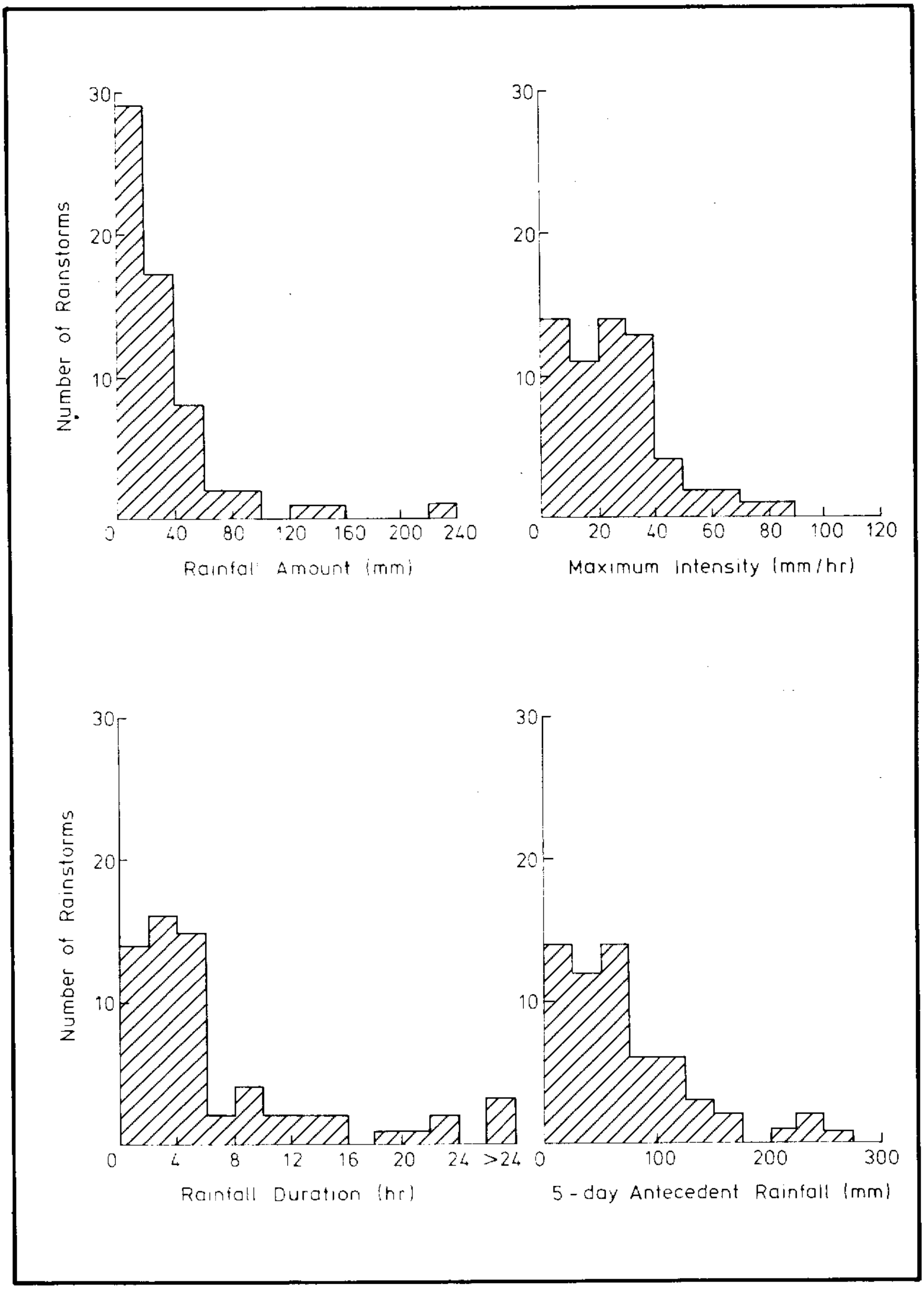



**Figure 17 - Statistics of the Rainstorms Used in the Study at Clear Water Bay Road**

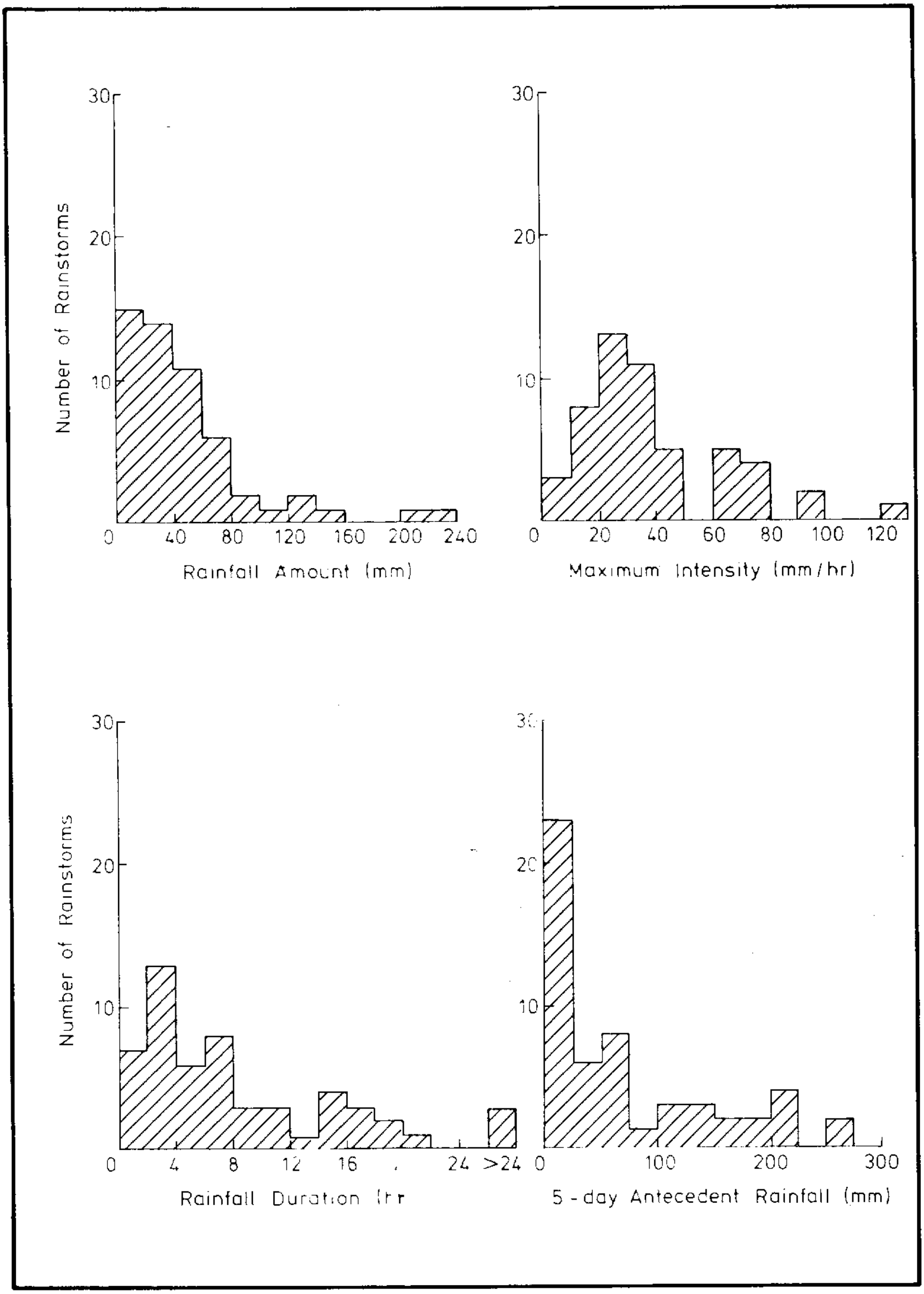



Figure 18 - Statistics of the Rainstorms Used in the Study at Chuk Yuen

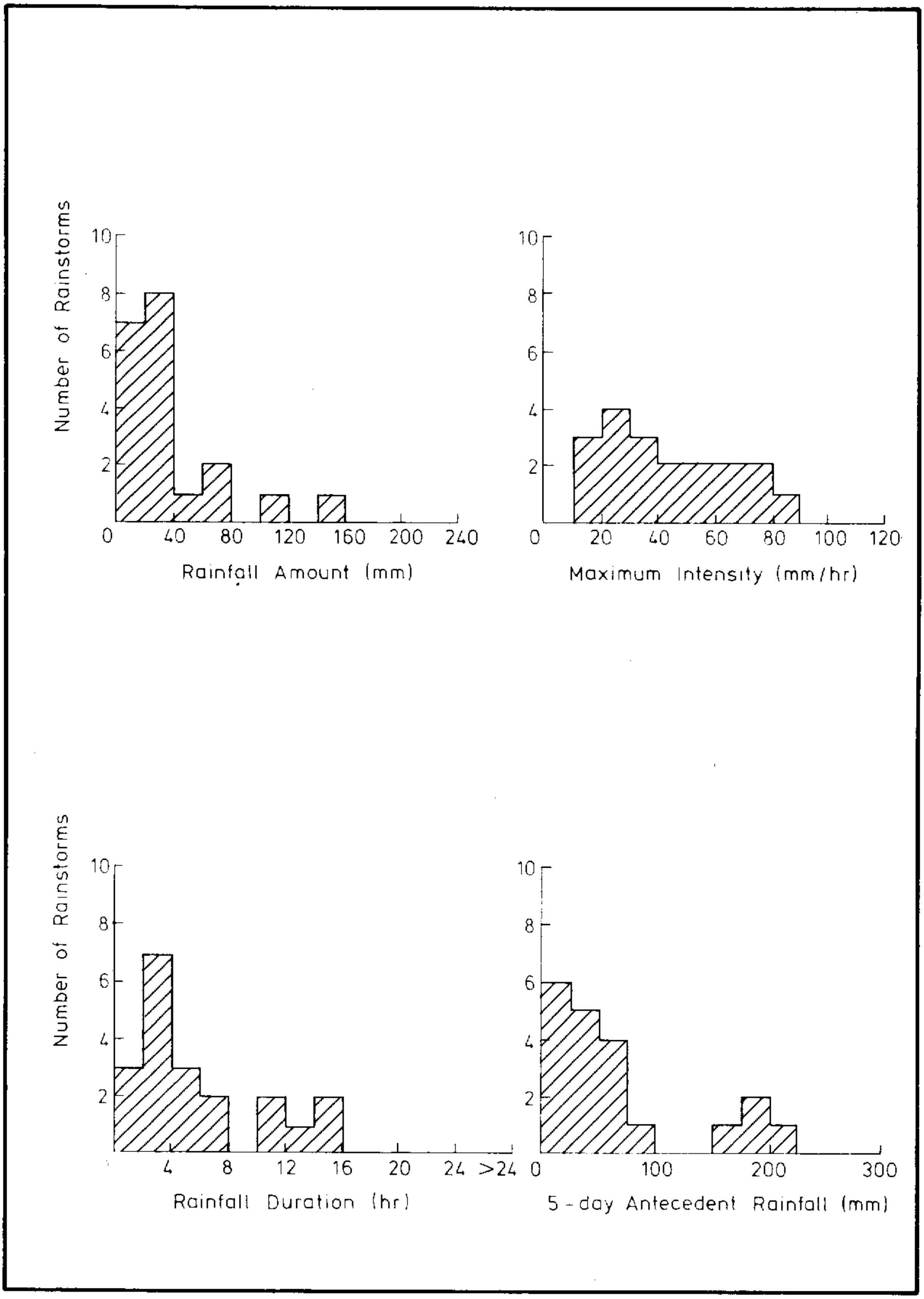



Figure 19 - Statistics of the Rainstorms Used in the Study at Tsuen Wan

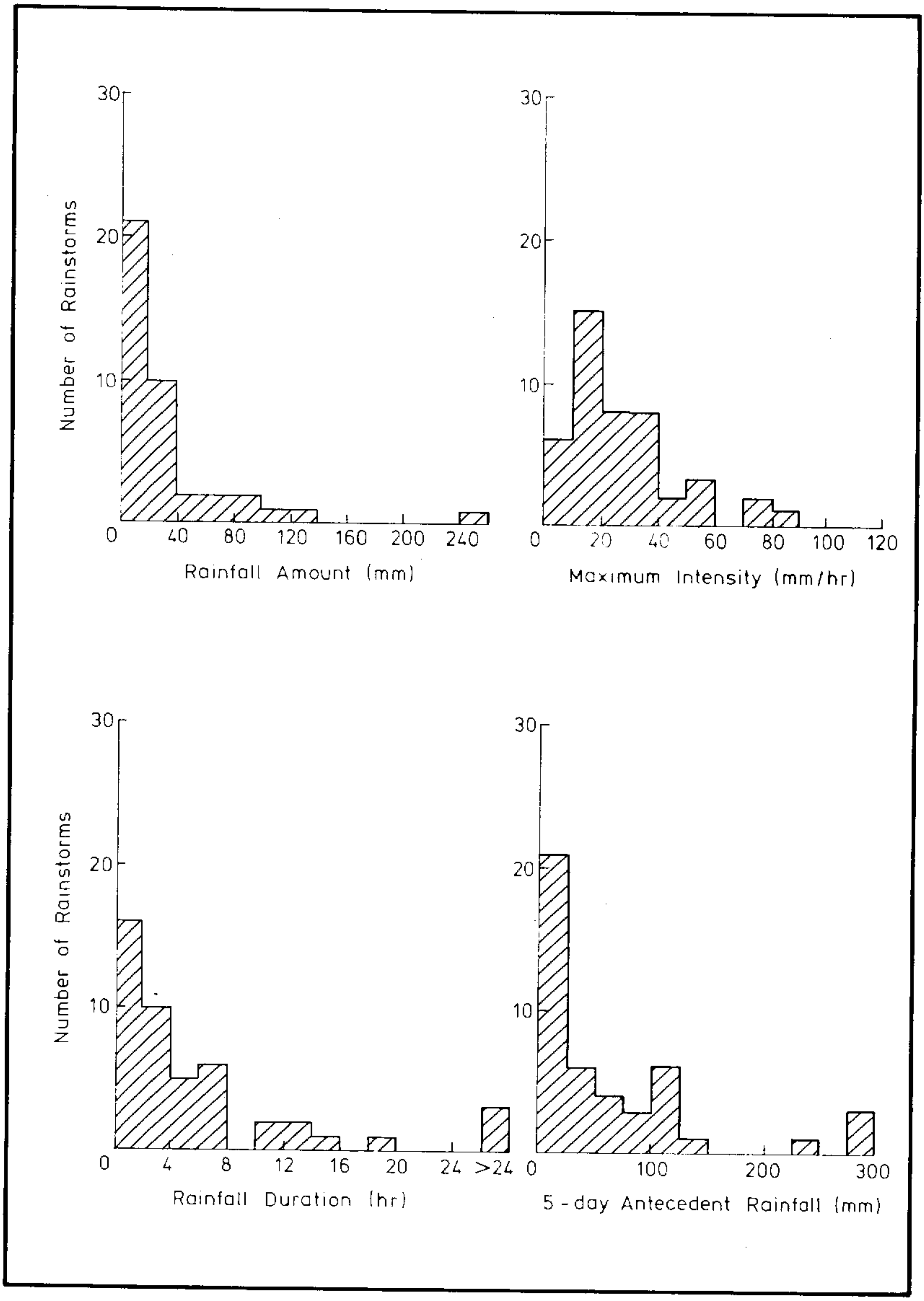



Figure 20 - Statistics of the Rainstorms Used in the Study at Kohima Barracks

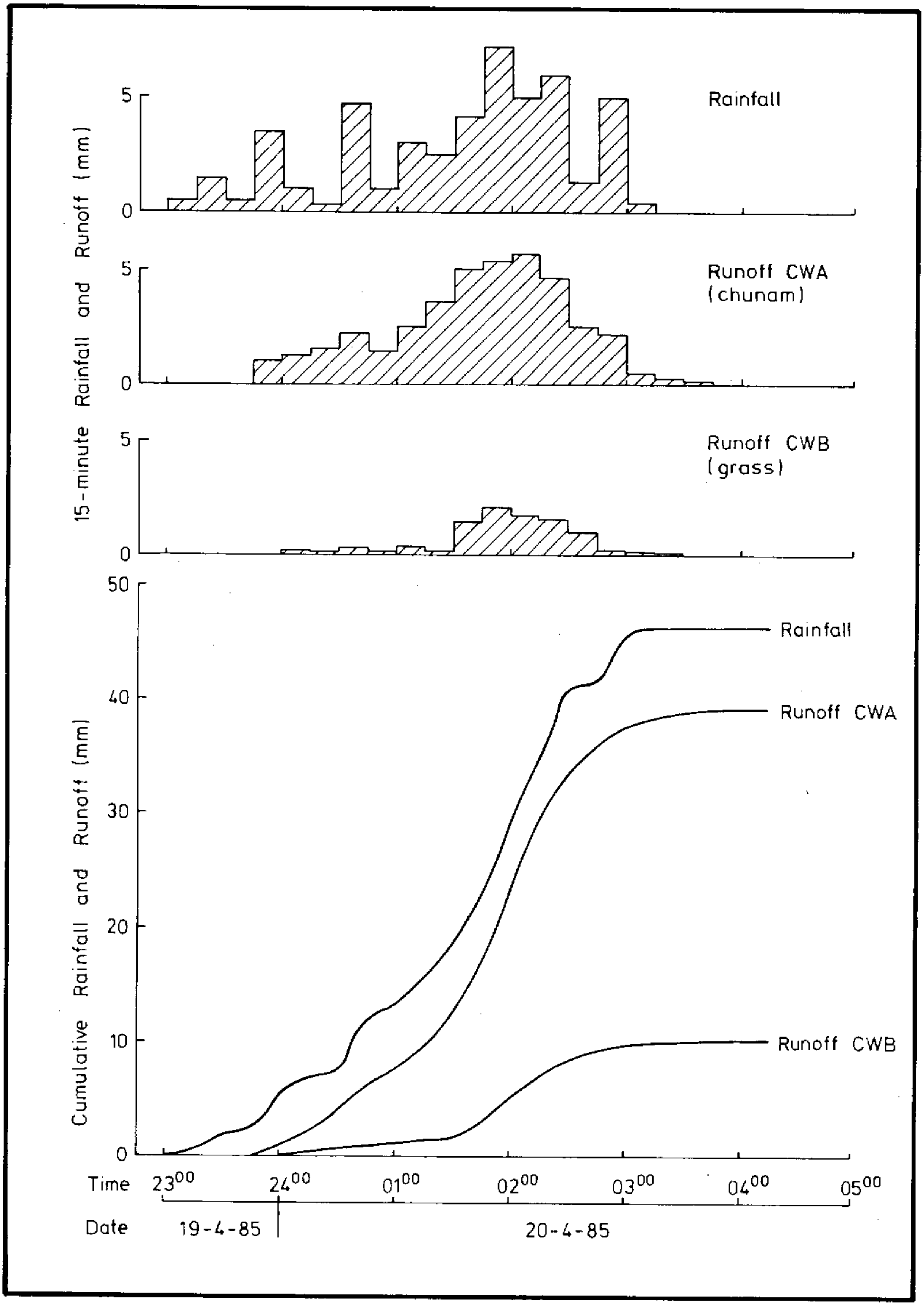



Figure 21 - Intensity and Cumulative Amount of Rainfall and Runoff at Clear Water Bay Road Slopes

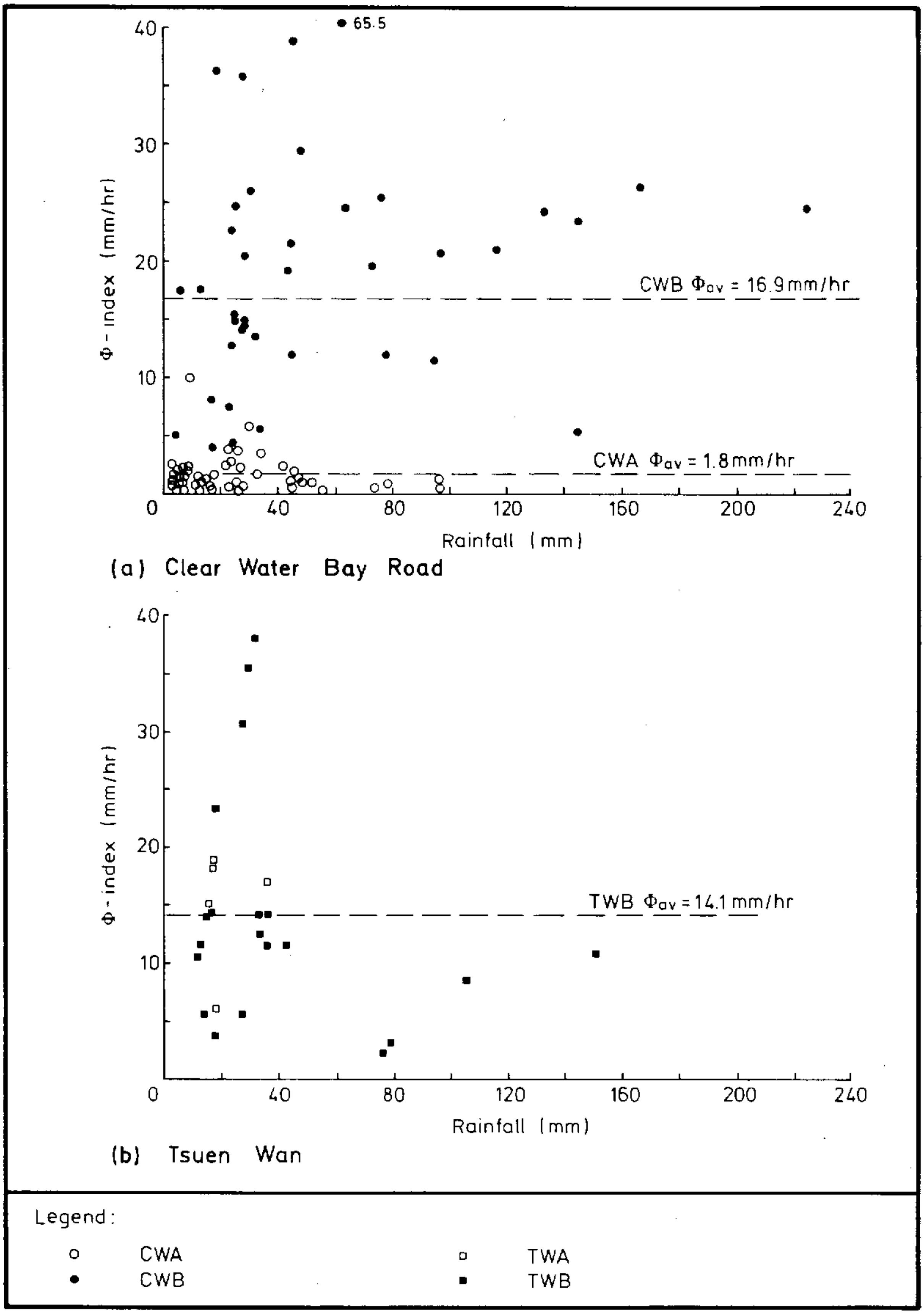



Figure 22 - Ø-index Values for Various Rainfall Amounts at the Sites at Clear Water Bay Road and Tsuen Wan

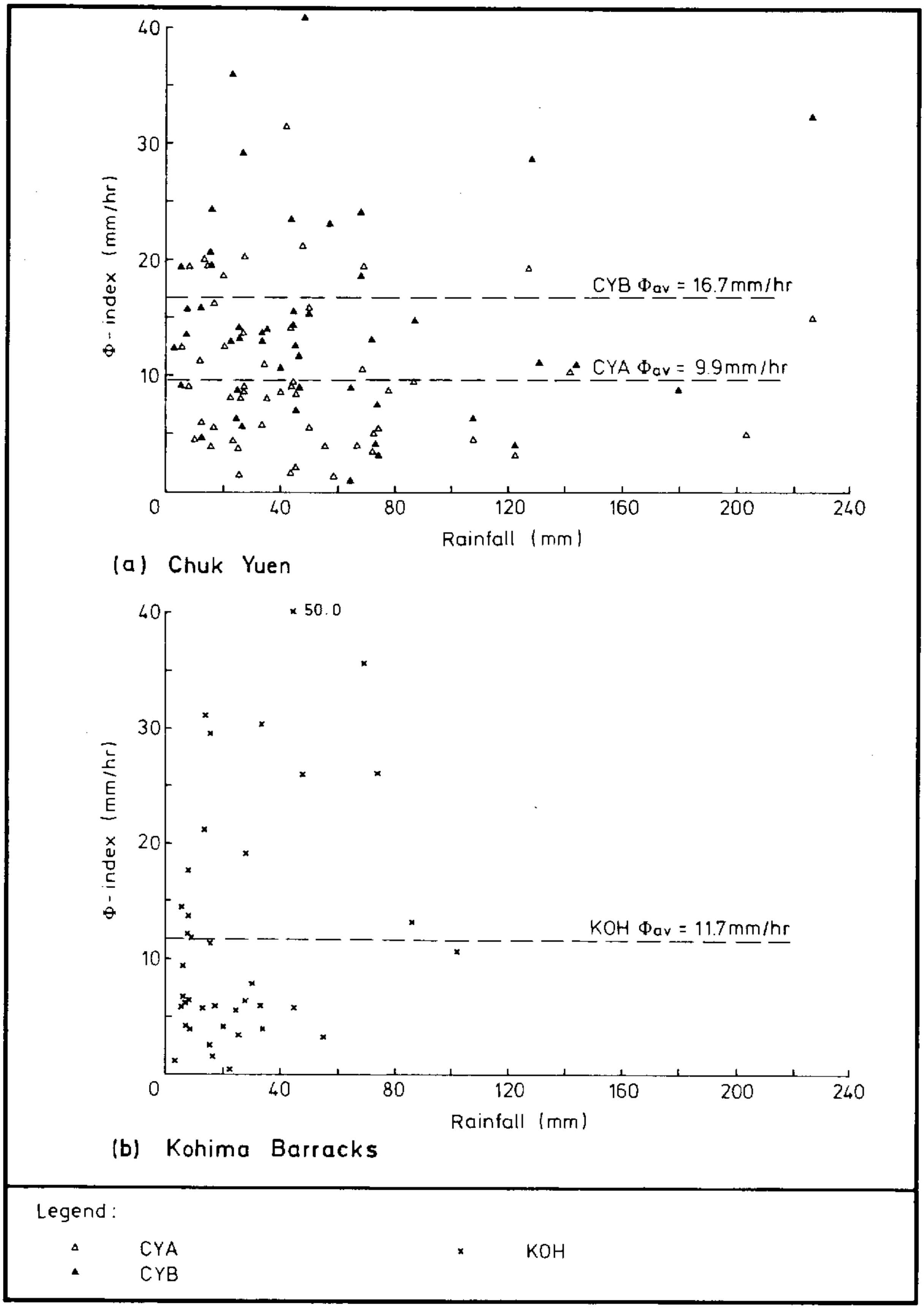



Figure 23 – ϕ-index Values for Various Rainfall Amounts at the Sites at Chuk Yuen and Kohima Barracks

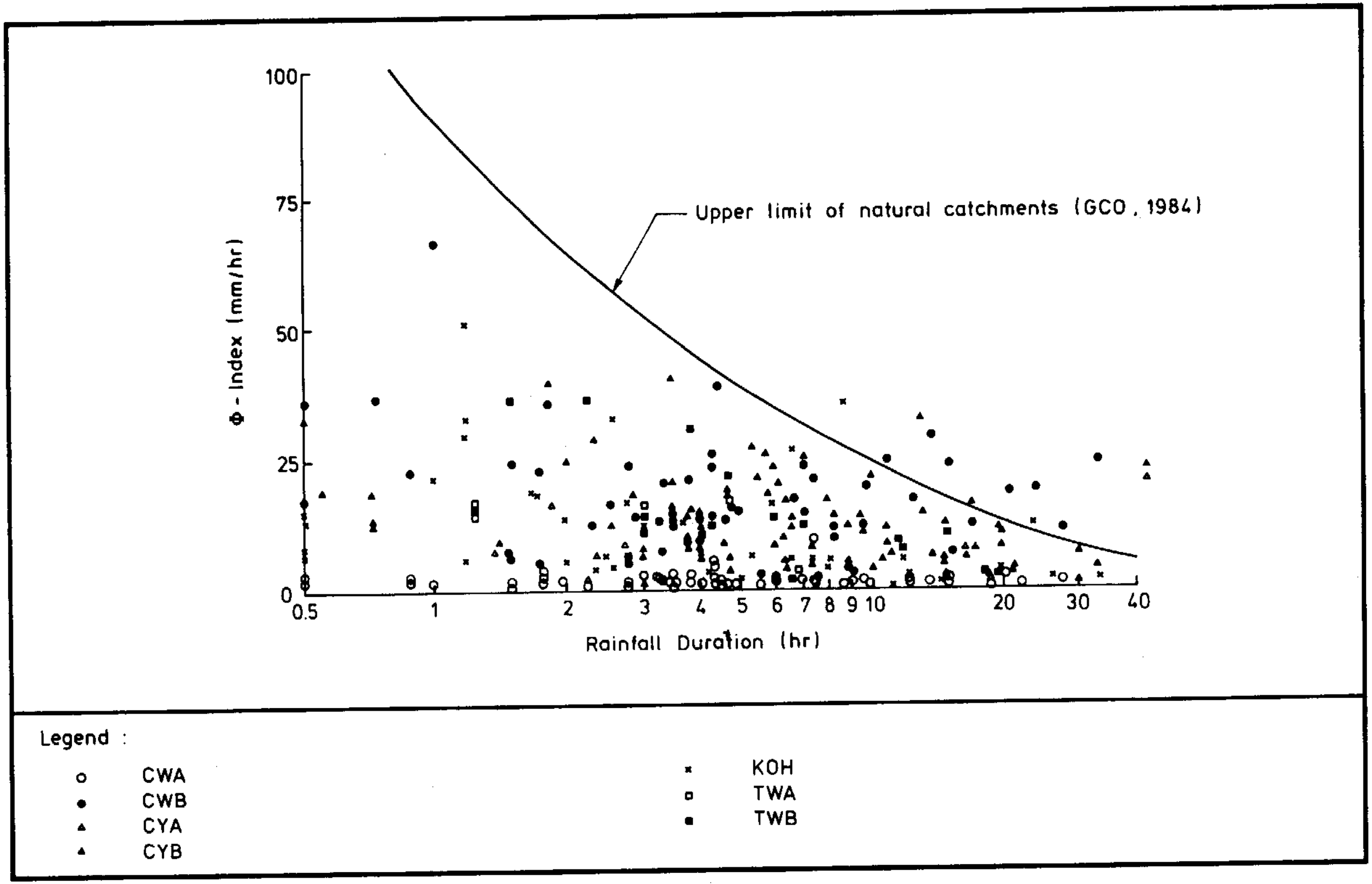



Figure 24 – Variation of ∅-index with Rainfall Duration for All Sites

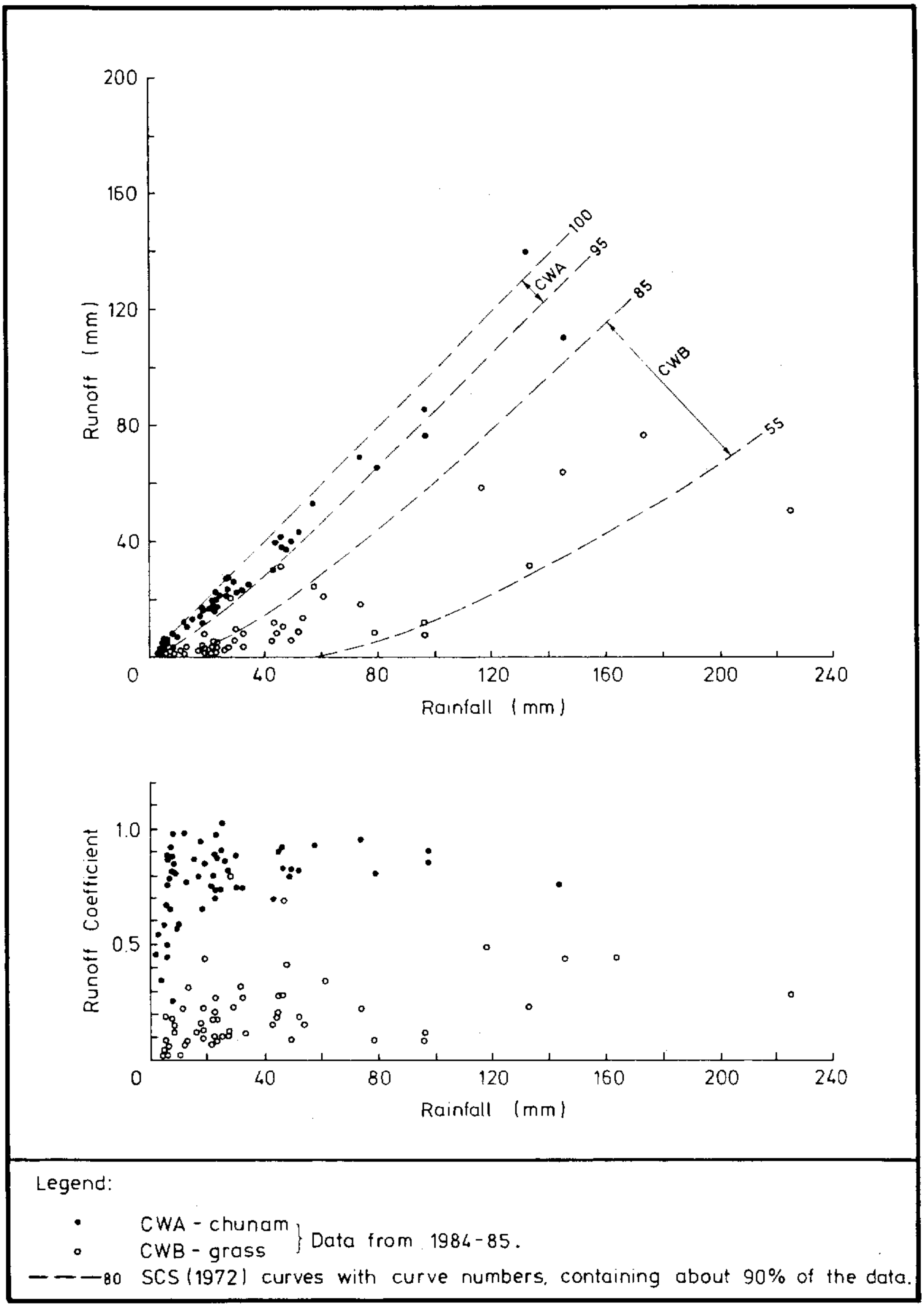



**Figure 25 – Relationships between Rainfall, Runoff and Runoff Coefficient for the Two Plots on Clear Water Bay Road**

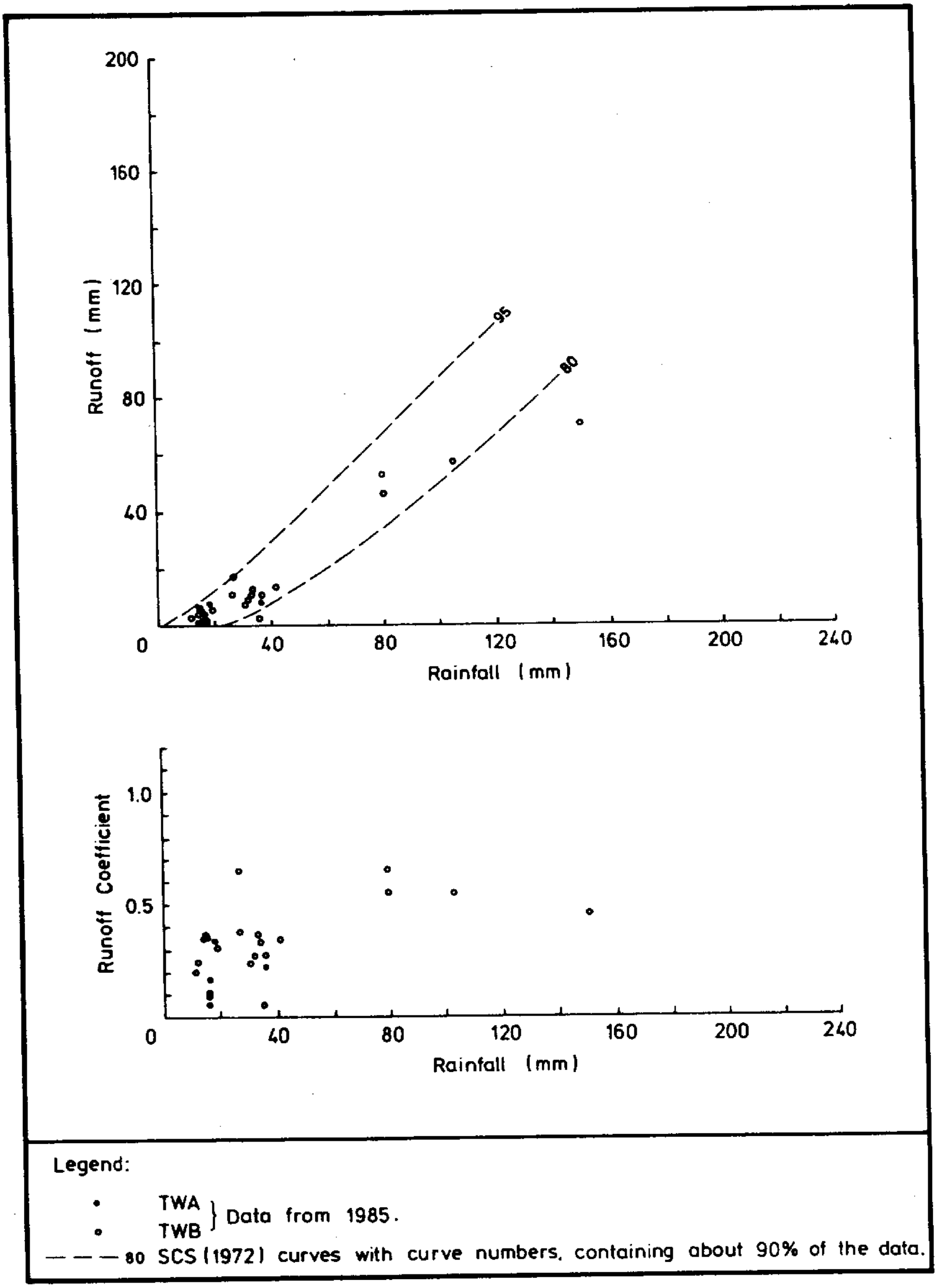



Figure 26 - Relationships between Rainfall, Runoff and Runoff Coefficient for the Two Plots in Tsuen Wan

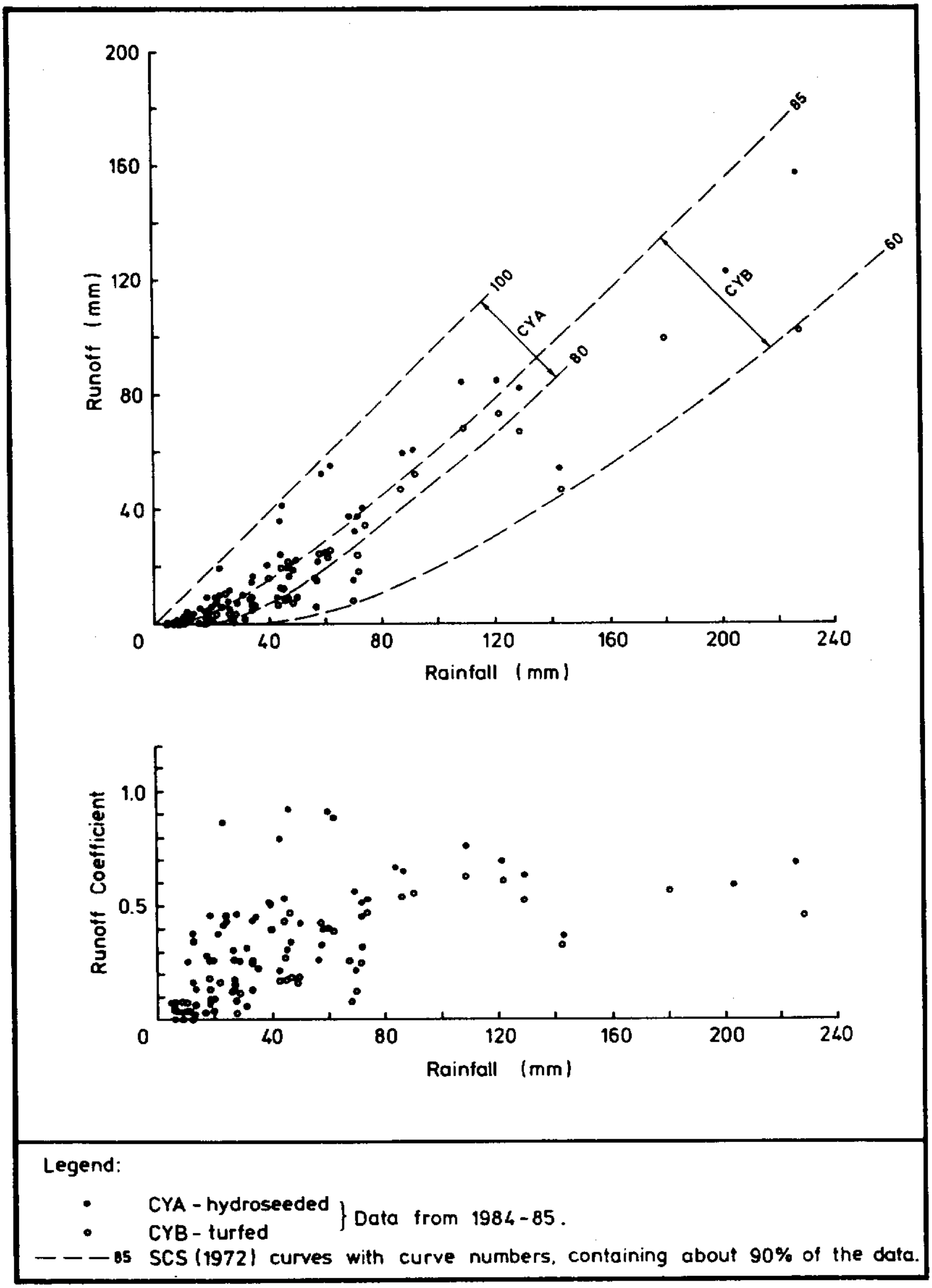



Figure 27 - Relationships between Rainfall, Runoff and Runoff Coefficient for the Two Plots in Chuk Yuen

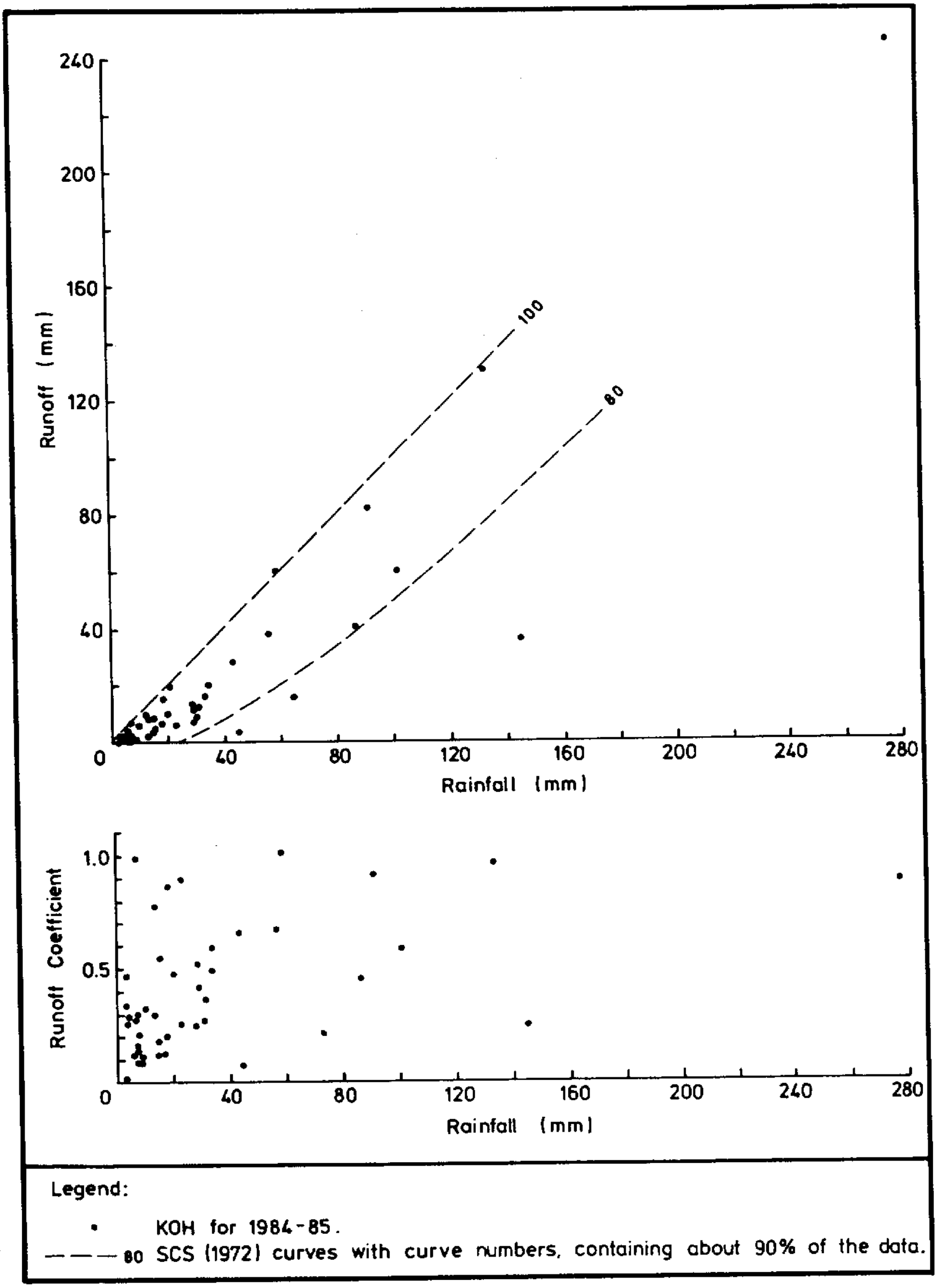
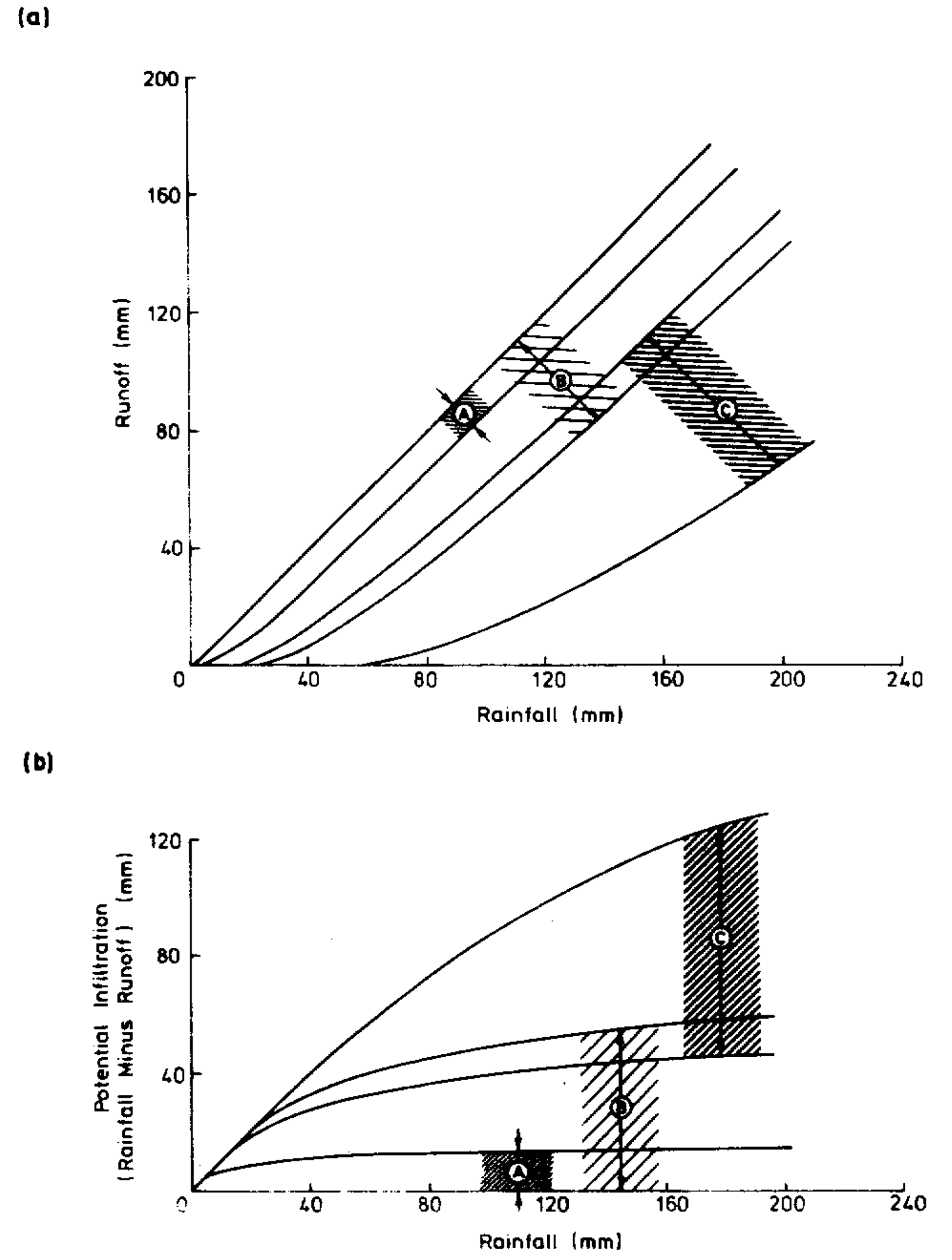



Figure 28 - Relationships between Rainfall, Runoff and Runoff Coefficient for the Plot in Kohima Barracks




Legend

| | |
|---|---|
| Ⓐ | Chunam (CWA) |
| Ⓑ | Hydroseeded (CYA)<br>Trees (TWB)<br>Turfed (KOH)* |
| Ⓒ | Turfed (CYB & CWB) |
| * | Volcanic soil fill slope, all others are weathered granite cut slopes. |

Note :
(1) The runoff curves take the form of SCS curves in Figure 7.
(2) The limits shown cover about 90% of all data for each slope in Table 6.
(3) Specific details of the covers are provided in Tables 2 to 4.
(4) Slope TWA did not have sufficient data to be included.

Figure 29 - Summary of Rainfall-Runoff Relationships for Various Surface Covers and Soil Types

# LIST OF PLATES

Negative No. HQ 8602110 Date: 9.7.1986

Plate 1 - Slope Clear Water Bay A (CWA)

Negative No. HQ 8602114 Date: 9.7.1986

Plate 2 - Slope Clear Water Bay B (CWB)

Negative No. HQ 8602136 Date: 9.7.1986

Plate 3 - Slope Tsuen Wan A (TWA)

Negative No. HQ 8602305 Date: 22.7.1986

Plate 4 - Slope Tsuen Wan B (TWB)

Negative No. HQ 8602122 Date: 9.7.1986

Plate 5 - Slope Chuk Yuen A (CYA)

Negative No. HQ 8602118 Date: 9.7.1986

Plate 6 - Slope Chuk Yuen B (CYB)

Negative No. HQ 8602102 Date: 9.7.1986

Plate 7 - Slope Kohima Barracks (KOH)

Negative No. SP 8601018 Date: 21.5.1986

Plate 8 - Calibration of Weir

# APPENDIX A

## SUMMARY OF RAINFALL AND RUNOFF DATA

# APPENDIX A

## LIST OF TABLES

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 1 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 27 APR 84 | 20:45 | 2.25 | 45.5 | 20.2 | 96.0 | 1.5 | 68.5 | - | 31.2 | - | 0.686 |
| 17 MAY 84 | 05:00 | 8.25 | 53.5 | 6.5 | 28.0 | 68.0 | 117.0 | - | 12.3 | - | 0.230 |
| 18 MAY 84 | 19:00 | 1.50 | 27.0 | 18.0 | 72.0 | 151.0 | 195.5 | - | 21.6 | - | 0.802 |
| 16 JUN 84 | 01:30 | 7.00 | 173.5 | 24.8 | 70.0 | 24.5 | 123.0 | - | 76.4 | - | 0.440 |
| 20 JUN 84 | 15:45 | 3.50 | 7.5 | 2.1 | 22.0 | 242.5 | 282.5 | 7.4 | - | 0.980 | - |
| 29 JUN 84 | 07:00 | 1.50 | 5.5 | 3.7 | 8.0 | 95.0 | 406.0 | 3.6 | - | 0.662 | - |
| 30 JUN 84 | 07:30 | 0.50 | 2.5 | 5.0 | 6.0 | 100.5 | 411.0 | 1.0 | - | 0.396 | - |
| 1 JUL 84 | 03:00 | 2.75 | 6.5 | 2.4 | 18.0 | 42.5 | 411.5 | 4.7 | - | 0.729 | - |
| 3 JUL 84 | 06:15 | 3.00 | 26.5 | 8.8 | 34.0 | 32.0 | 228.0 | 22.9 | - | 0.863 | - |
| 8 JUL 84 | 09:30 | 0.50 | 6.0 | 12.0 | 22.0 | 39.5 | 152.5 | 4.9 | - | 0.812 | - |
| 1 AUG 84 | 13:15 | 0.75 | 19.5 | 26.0 | 46.0 | 6.5 | 9.0 | - | 2.3 | - | 0.118 |
| 9 AUG 84 | 22:00 | 2.50 | 11.5 | 4.6 | 28.0 | 111.5 | 111.5 | - | 2.5 | - | 0.217 |

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 2 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 10 AUG 84 | 03:00 | 0.50 | 6.5 | 12.0 | 22.0 | 55.0 | 136.5 | - | 0.6 | - | 0.097 |
| 1 SEP 84 | 04:30 | 4.50 | 22.0 | 4.9 | 30.0 | 5.0 | 37.5 | 19.7 | 4.7 | 0.894 | 0.211 |
| 1 SEP 84 | 12:45 | 18.50 | 79.5 | 4.3 | 26.0 | 27.9 | 59.5 | 64.5 | 8.5 | 0.811 | 0.107 |
| 4 SEP 84 | 03:00 | 1.75 | 5.5 | 3.1 | 8.0 | 107.5 | 138.0 | 3.6 | - | 0.653 | - |
| 16 SEP 84 | 06:00 | 5.50 | 73.5 | 13.4 | 38.0 | 5.0 | 125.5 | 70.1 | - | 0.953 | - |
| 16 SEP 84 | 06:00 | 6.50 | 74.0 | 13.4 | 38.0 | 5.0 | 125.5 | - | 17.0 | - | 0.230 |
| 19 SEP 84 | 13:00 | 2.00 | 15.0 | 7.5 | 32.0 | 79.5 | 100.5 | 13.1 | - | 0.871 | - |
| 20 SEP 84 | 04:30 | 9.00 | 19.0 | 2.1 | 16.0 | 92.0 | 109.0 | 16.1 | 8.3 | 0.846 | 0.438 |
| 25 SEP 84 | 23:45 | 4.25 | 34.5 | 8.1 | 34.0 | 19.0 | 116.0 | 25.0 | 3.6 | 0.725 | 0.105 |
| 26 SEP 84 | 20:45 | 1.00 | 5.5 | 5.5 | 12.0 | 35.0 | 151.0 | 4.8 | - | 0.871 | - |
| 10 OCT 84 | 21:45 | 7.50 | 144.5 | 19.3 | 80.0 | 6.0 | 13.5 | 110.2 | 63.2 | 0.763 | 0.437 |
| 17 OCT 84 | 12:00 | 3.75 | 19.0 | 5.1 | 24.0 | 2.0 | 153.0 | 12.0 | 4.5 | 0.633 | 0.236 |

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 3 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 10 APR 85 | 10:30 | 12.00 | 57.0 | 4.8 | 52.0 | 2.0 | 8.0 | 53.4 | 24.3 | 0.936 | 0.425 |
| 11 APR 85 | 00:00 | 4.25 | 30.5 | 7.2 | 62.0 | 59.0 | 65.0 | 22.6 | 9.9 | 0.742 | 0.325 |
| 12 APR 85 | 12:45 | 4.75 | 29.5 | 6.2 | 24.0 | 90.5 | 96.5 | 26.2 | 6.5 | 0.889 | 0.221 |
| 12 APR 85 | 22:30 | 8.75 | 10.5 | 1.2 | 4.0 | 120.0 | 126.0 | 6.1 | 0.6 | 0.578 | 0.058 |
| 13 APR 85 | 13:15 | 3.50 | 22.5 | 6.4 | 30.0 | 130.5 | 136.5 | 19.5 | 3.9 | 0.868 | 0.172 |
| 14 APR 85 | 02:30 | 1.50 | 5.0 | 3.0 | 8.0 | 153.0 | 153.0 | 4.0 | 0.5 | 0.792 | 0.094 |
| 19 APR 85 | 23:00 | 4.25 | 46.0 | 10.8 | 28.0 | 9.0 | 162.0 | 38.4 | 10.4 | 0.835 | 0.225 |
| 2 MAY 85 | 02:00 | 6.00 | 8.0 | 1.3 | 4.0 | 0.0 | 39.5 | 1.9 | 1.0 | 0.236 | 0.126 |
| 2 MAY 85 | 13:30 | 5.50 | 12.0 | 2.2 | 6.0 | 8.5 | 8.5 | 11.9 | 3.6 | 0.992 | 0.301 |
| 28 MAY 85 | 04:00 | 12.50 | 47.5 | 3.8 | 26.0 | 2.0 | 16.0 | 37.6 | - | 0.792 | - |
| 30 MAY 85 | 19:00 | 3.25 | 5.5 | 2.5 | 12.0 | 53.5 | 67.0 | 2.7 | 1.0 | 0.496 | 0.178 |
| 31 MAY 85 | 01:15 | 0.75 | 8.5 | 11.3 | 28.0 | 61.5 | 75.5 | 7.0 | 1.3 | 0.821 | 0.156 |

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 4 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 31 MAY 85 | 07:00 | 15.00 | 21.0 | 1.4 | 12.0 | 70.5 | 84.5 | 15.9 | 1.6 | 0.758 | 0.074 |
| 3 JUN 85 | 17:45 | 2.75 | 5.5 | 2.0 | 6.0 | 62.5 | 125.5 | 2.4 | 0.1 | 0.442 | 0.020 |
| 4 JUN 85 | 02:30 | 2.75 | 23.0 | 8.4 | 34.0 | 64.5 | 131.5 | 22.6 | 4.4 | 0.981 | 0.193 |
| 7 JUN 85 | 04:15 | 0.75 | 2.5 | 3.3 | 6.0 | 37.5 | 146.0 | 0.9 | - | 0.352 | - |
| 7 JUN 85 | 11:45 | 3.50 | 17.5 | 5.0 | 20.0 | 40.0 | 148.5 | 14.0 | 2.1 | 0.799 | 0.121 |
| 24 JUN 85 | 08:45 | 32.75 | 225.5 | 6.9 | 64.0 | 24.0 | 48.0 | - | 46.7 | - | 0.207 |
| 26 JUN 85 | 00:00 | 3.75 | 117.5 | 31.3 | 98.0 | 105.0 | 132.0 | - | 57.6 | - | 0.490 |
| 3 JUL 85 | 01:30 | 13.50 | 49.0 | 3.6 | 40.0 | 61.5 | 391.5 | 40.4 | 4.8 | 0.824 | 0.098 |
| 8 JUL 85 | 00:30 | 4.25 | 22.5 | 5.3 | 46.0 | 49.0 | 377.5 | 15.7 | 6.1 | 0.699 | 0.269 |
| 8 JUL 85 | 15:30 | 15.00 | 52.0 | 3.5 | 42.0 | 71.5 | 400.0 | 43.1 | 8.9 | 0.829 | 0.172 |
| 18 JUL 85 | 07:15 | 1.75 | 22.0 | 12.6 | 32.0 | 6.5 | 65.5 | 17.5 | 2.2 | 0.795 | 0.101 |
| 18 JUL 85 | 14:00 | 3.25 | 13.0 | 4.0 | 18.0 | 28.5 | 87.5 | 10.0 | 1.2 | 0.772 | 0.095 |

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 5 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 19 JUL 85 | 02:00 | 1.75 | 4.5 | 2.6 | 6.0 | 41.5 | 51.5 | 2.3 | 0.1 | 0.504 | 0.031 |
| 19 JUL 85 | 09:30 | 1.75 | 27.0 | 15.4 | 50.0 | 46.0 | 56.0 | 22.1 | 3.5 | 0.819 | 0.130 |
| 19 JUL 85 | 13:45 | 3.75 | 4.5 | 1.2 | 4.0 | 73.0 | 83.0 | 2.6 | 0.1 | 0.584 | 0.016 |
| 20 JUL 85 | 00:15 | 8.25 | 13.5 | 1.6 | 14.0 | 72.0 | 88.0 | - | 1.1 | - | 0.079 |
| 26 JUL 85 | 11:00 | 4.50 | 44.5 | 9.9 | 84.0 | 0.0 | 94.0 | 40.6 | 12.1 | 0.913 | 0.272 |
| 12 AUG 85 | 15:00 | 20.25 | 42.5 | 2.1 | 36.0 | 28.5 | 42.5 | 28.9 | 6.4 | 0.680 | 0.151 |
| 13 AUG 85 | 14:15 | 9.50 | 22.5 | 2.4 | 20.0 | 71.0 | 85.0 | 16.4 | 1.7 | 0.727 | 0.077 |
| 14 AUG 85 | 04:30 | 4.75 | 6.0 | 1.3 | 18.0 | 83.0 | 107.5 | 5.5 | 0.4 | 0.917 | 0.062 |
| 14 AUG 85 | 12:45 | 9.75 | 24.0 | 2.4 | 28.0 | 89.0 | 113.5 | 21.7 | 2.0 | 0.905 | 0.081 |
| 15 AUG 85 | 03:15 | 4.00 | 6.5 | 1.6 | 10.0 | 112.5 | 137.5 | 5.6 | 0.5 | 0.858 | 0.069 |
| 15 AUG 85 | 11:30 | 1.50 | 5.5 | 3.7 | 8.0 | 119.0 | 144.0 | 4.2 | 0.1 | 0.764 | 0.025 |
| 16 AUG 85 | 03:15 | 3.25 | 44.0 | 13.5 | 48.0 | 124.5 | 149.5 | 39.9 | 7.7 | 0.907 | 0.176 |

Table A1 - Summary of Rainfall and Runoff Data for Two Plots on Clear Water Bay Road (Sheet 6 of 6)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | CWA | CWB | CWA | CWB |
| 16 AUG 85 | 11:30 | 4.00 | 26.5 | 6.6 | 20.0 | 168.5 | 193.5 | 27.4 | 2.3 | 1.035 | 0.087 |
| 19 AUG 85 | 15:30 | 1.00 | 60.5 | 60.5 | 126.0 | 113.0 | 210.0 | - | 20.5 | - | 0.340 |
| 21 AUG 85 | 00:00 | 7.50 | 19.0 | 2.5 | 6.0 | 132.5 | 269.0 | - | 1.9 | - | 0.101 |
| 21 AUG 85 | 13:00 | 22.25 | 96.5 | 4.3 | 32.0 | 132.5 | 269.5 | 86.8 | 7.1 | 0.900 | 0.074 |
| 25 AUG 85 | 21:00 | 10.25 | 132.0 | 12.9 | 60.0 | 128.5 | 385.5 | 140.2 | 30.7 | 1.062 | 0.233 |
| 26 AUG 85 | 14:30 | 27.00 | 96.0 | 3.6 | 38.0 | 260.5 | 517.5 | 75.9 | 10.5 | 0.791 | 0.109 |
| 28 AUG 85 | 02:00 | 7.25 | 17.5 | 2.4 | 26.0 | 240.5 | 581.5 | 16.6 | 2.9 | 0.949 | 0.163 |
| 20 SEP 85 | 23:30 | 3.50 | 32.0 | 9.1 | 32.0 | 32.5 | 272.0 | 24.0 | 8.8 | 0.749 | 0.275 |
| 21 SEP 85 | 04:00 | 0.75 | 2.5 | 3.3 | 4.0 | 64.5 | 239.0 | 1.4 | - | 0.548 | - |
| 21 SEP 85 | 07:15 | 2.25 | 5.5 | 2.4 | 12.0 | 67.0 | 241.5 | 4.8 | - | 0.880 | - |
| 21 SEP 85 | 10:45 | 0.75 | 10.0 | 13.3 | 34.0 | 72.5 | 247.0 | 5.9 | - | 0.585 | - |

Table A2 - Summary of Rainfall and Runoff Data for Two Plots in Tsuen Wan (Sheet 1 of 2)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | TWA | TWB | TWA | TWB |
| 29 MAR 85 | 00:30 | 4.75 | 18.0 | 3.8 | 18.0 | 6.0 | 10.0 | 5.5 | - | 0.304 | - |
| 29 MAR 85 | 00:30 | 15.00 | 35.0 | 2.3 | 18.0 | 6.0 | 10.0 | - | 2.1 | - | 0.059 |
| 19 APR 85 | 23:30 | 3.00 | 35.5 | 11.9 | 36.0 | 20.0 | 253.5 | 8.2 | 10.3 | 0.230 | 0.289 |
| 28 MAY 85 | 05:00 | 2.25 | 31.0 | 14.0 | 74.0 | 2.5 | 2.5 | - | 8.9 | - | 0.288 |
| 28 MAY 85 | 13:30 | 2.75 | 26.0 | 9.5 | 26.0 | 33.5 | 33.5 | - | 17.1 | - | 0.656 |
| 31 MAY 85 | 11:45 | 6.25 | 18.5 | 3.0 | 18.0 | 74.0 | 74.0 | - | 5.9 | - | 0.318 |
| 5 JUN 85 | 09:30 | 4.75 | 16.0 | 3.4 | 30.0 | 29.0 | 94.0 | 2.7 | 1.7 | 0.171 | 0.104 |
| 7 JUN 85 | 12:15 | 1.25 | 16.0 | 12.8 | 22.0 | 24.5 | 113.0 | 1.0 | 1.9 | 0.060 | 0.116 |
| 13 JUN 85 | 05:00 | 1.25 | 14.5 | 11.6 | 36.0 | 1.5 | 71.0 | 5.1 | 5.4 | 0.354 | 0.370 |
| 25 JUN 85 | 00:15 | 11.25 | 150.0 | 13.5 | 68.0 | 69.0 | 88.0 | - | 69.6 | - | 0.464 |
| 25 JUN 85 | 23:30 | 4.25 | 33.5 | 7.9 | 54.0 | 220.5 | 239.5 | - | 11.4 | - | 0.341 |
| 18 JUL 85 | 14:00 | 3.00 | 12.0 | 4.0 | 22.0 | 35.5 | 125.5 | - | 3.0 | - | 0.251 |

Table A2 - Summary of Rainfall and Runoff Data for Two Plots in Tsuen Wan (Sheet 2 of 2)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | TWA | TWB | TWA | TWB |
| 19 JUL 85 | 13:45 | 6.00 | 32.5 | 5.4 | 48.0 | 31.0 | 112.5 | - | 12.2 | - | 0.376 |
| 20 JUL 85 | 00:45 | 7.00 | 14.5 | 2.1 | 14.0 | 66.0 | 148.0 | - | 5.2 | - | 0.360 |
| 21 AUG 85 | 14:45 | 18.75 | 79.5 | 4.3 | 44.0 | 224.5 | 338.0 | - | 45.3 | - | 0.570 |
| 25 AUG 85 | 21:00 | 11.75 | 104.5 | 9.1 | 84.0 | 166.0 | 426.0 | - | 57.4 | - | 0.549 |
| 26 AUG 85 | 22:15 | 19.75 | 78.5 | 4.0 | 64.0 | 238.0 | 536.0 | - | 52.1 | - | 0.664 |
| 19 SEP 85 | 11:45 | 3.75 | 26.0 | 6.9 | 72.0 | 5.0 | 239.0 | - | 10.3 | - | 0.395 |
| 21 SEP 85 | 00:00 | 3.00 | 42.5 | 13.7 | 32.0 | 29.5 | 162.0 | - | 14.3 | - | 0.336 |
| 21 SEP 85 | 08:30 | 4.00 | 10.5 | 2.6 | 16.0 | 70.5 | 203.0 | - | 2.2 | - | 0.209 |
| 24 SEP 85 | 04:15 | 1.50 | 29.5 | 19.7 | 54.0 | 87.5 | 122.5 | - | 7.2 | - | 0.244 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Table A3 - Summary of Rainfall and Runoff Data for Two Plots in Chuk Yuen (Sheet 1 of 5)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | CYA | CYB | CYA | CYB |
| 27 APR 84 | 20:00 | 2.25 | 45.0 | 20.0 | 74.0 | 3.0 | 60.0 | 40.9 | 19.2 | 0.910 | 0.428 |
| 17 MAY 84 | 05:15 | 6.00 | 27.0 | 4.5 | 24.0 | 29.5 | 70.5 | 4.6 | 1.0 | 0.170 | 0.036 |
| 18 MAY 84 | 12:00 | 10.00 | 26.0 | 2.6 | 38.0 | 62.0 | 103.0 | 12.2 | 4.1 | 0.471 | 0.158 |
| 5 JUN 84 | 12:15 | 3.50 | 48.5 | 13.9 | 66.0 | 60.0 | 257.0 | 19.4 | 9.7 | 0.400 | 0.200 |
| 16 JUN 84 | 01:00 | 12.50 | 226.5 | 18.1 | 122.0 | 15.0 | 127.0 | 155.5 | 101.1 | 0.686 | 0.446 |
| 21 JUN 84 | 16:15 | 3.00 | 22.5 | 7.5 | 42.0 | 277.0 | 295.5 | 19.2 | 10.7 | 0.853 | 0.473 |
| 25 JUN 84 | 10:30 | 4.75 | 44.0 | 9.3 | 44.0 | 57.0 | 333.5 | 35.7 | 23.9 | 0.811 | 0.543 |
| 8 JUL 84 | 09:45 | 30.00 | 62.0 | 2.1 | 36.0 | 8.5 | 113.5 | 54.6 | 24.5 | 0.880 | 0.396 |
| 4 AUG 84 | 04:45 | 7.00 | 59.5 | 8.5 | 66.0 | 0.5 | 2.5 | 53.0 | 23.8 | 0.891 | 0.399 |
| 4 AUG 84 | 17:15 | 17.75 | 45.0 | 2.5 | 24.0 | 60.0 | 62.0 | 14.4 | 8.7 | 0.321 | 0.194 |
| 9 AUG 84 | 22:15 | 5.50 | 28.5 | 5.2 | 36.0 | 111.5 | 113.5 | 7.4 | 3.3 | 0.259 | 0.115 |
| 10 AUG 84 | 21:45 | 15.00 | 108.5 | 7.2 | 72.0 | 70.0 | 147.0 | 82.9 | 69.8 | 0.764 | 0.643 |

Table A3 - Summary of Rainfall and Runoff Data for Two Plots in Chuk Yuen (Sheet 2 of 5)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CYA | CYB | CYA | CYB |
| 12 AUG 84 | 11:45 | 4.75 | 18.5 | 3.9 | 30.0 | 155.5 | 267.0 | 8.8 | 2.7 | 0.473 | 0.143 |
| 16 AUG 84 | 22:45 | 2.75 | 20.0 | 7.3 | 40.0 | 148.0 | 299.0 | 5.2 | 1.8 | 0.261 | 0.092 |
| 20 AUG 84 | 10:45 | 6.25 | 23.0 | 3.7 | 22.0 | 34.0 | 243.5 | 10.3 | 6.1 | 0.448 | 0.265 |
| 20 AUG 84 | 21:15 | 15.50 | 57.5 | 3.7 | 14.0 | 57.0 | 266.5 | 21.2 | 15.3 | 0.368 | 0.266 |
| 31 AUG 84 | 19:15 | 2.75 | 9.0 | 3.3 | 12.0 | 2.0 | 106.5 | 0.8 | 0.1 | 0.092 | 0.001 |
| 1 SEP 84 | 07:30 | 2.25 | 11.5 | 5.1 | 16.0 | 12.5 | 104.0 | 4.4 | 1.3 | 0.380 | 0.116 |
| 1 SEP 84 | 13:15 | 14.25 | 56.5 | 4.0 | 14.0 | 24.0 | 115.5 | 15.3 | 5.0 | 0.270 | 0.088 |
| 16 SEP 84 | 06:45 | 4.25 | 17.0 | 4.0 | 10.0 | 3.5 | 106.0 | 4.9 | 0.7 | 0.289 | 0.039 |
| 19 SEP 84 | 13:15 | 1.75 | 30.5 | 17.4 | 50.0 | 24.5 | 59.5 | 10.0 | 2.3 | 0.328 | 0.076 |
| 26 SEP 84 | 00:00 | 4.00 | 18.0 | 4.5 | 20.0 | 3.5 | 39.5 | 2.9 | 0.3 | 0.158 | 0.019 |
| 26 SEP 84 | 18:00 | 4.75 | 12.0 | 2.5 | 18.0 | 14.5 | 50.5 | 0.4 | 0.3 | 0.030 | 0.003 |
| 10 OCT 84 | 22:00 | 7.25 | 92.0 | 12.7 | 78.0 | 0.0 | 3.0 | 59.6 | 51.9 | 0.647 | 0.564 |

Table A3 - Summary of Rainfall and Runoff Data for Two Plots in Chuk Yuen (Sheet 3 of 5)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | CYA | CYA | CYA | CYB |
| 29 MAR 85 | 01:00 | 15.50 | 50.0 | 3.2 | 36.0 | 2.5 | 3.5 | 22.1 | 9.5 | 0.441 | 0.189 |
| 9 APR 85 | 10:00 | 9.00 | 71.5 | 7.9 | 38.0 | 0.5 | 60.0 | 36.9 | 18.5 | 0.516 | 0.258 |
| 10 APR 85 | 11:00 | 17.00 | 68.0 | 4.0 | 50.0 | 72.0 | 131.5 | 38.5 | 21.8 | 0.566 | 0.321 |
| 11 APR 85 | 02:15 | 2.00 | 19.0 | 9.5 | 38.0 | 119.5 | 177.0 | - | 3.4 | - | 0.178 |
| 12 APR 85 | 13:30 | 4.00 | 25.5 | 6.4 | 28.0 | 140.0 | 197.0 | 8.0 | 3.5 | 0.313 | 0.138 |
| 13 APR 85 | 13:15 | 3.00 | 21.5 | 7.2 | 26.0 | 174.5 | 230.0 | 8.1 | 4.1 | 0.378 | 0.190 |
| 19 APR 85 | 23:15 | 3.75 | 35.0 | 9.3 | 30.0 | 6.5 | 203.0 | 15.9 | 7.9 | 0.454 | 0.227 |
| 28 MAY 85 | 06:15 | 9.50 | 34.0 | 3.6 | 22.0 | 1.5 | 6.0 | 8.4 | 4.7 | 0.247 | 0.138 |
| 31 MAY 85 | 01:00 | 1.50 | 6.0 | 4.0 | 10.0 | 42.0 | 47.0 | 0.4 | 0.3 | 0.070 | 0.053 |
| 31 MAY 85 | 07:00 | 0.75 | 5.5 | 7.3 | 14.0 | 48.0 | 53.0 | 0.4 | 0.3 | 0.073 | 0.051 |
| 31 MAY 85 | 14:00 | 6.25 | 10.5 | 1.7 | 6.0 | 53.5 | 58.5 | 0.4 | 0.3 | 0.033 | 0.032 |
| 24 JUN 85 | 08:30 | 32.75 | 202.5 | 6.2 | 92.0 | 16.5 | 34.5 | 121.1 | - | 0.598 | - |

Table A3 - Summary of Rainfall and Runoff Data for Two Plots in Chuk Yuen (Sheet 4 of 5)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | CYA | CYB | CYA | CYB |
| 24 JUN 85 | 21:30 | 20.00 | 180.0 | 9.0 | 92.0 | 76.5 | 94.5 | - | 99.6 | - | 0.554 |
| 25 JUN 85 | 23:45 | 3.75 | 86.5 | 23.1 | 76.0 | 215.5 | 235.5 | 56.8 | 46.5 | 0.656 | 0.537 |
| 3 JUL 85 | 01:30 | 0.75 | 9.0 | 12.0 | 20.0 | 2.5 | 310.5 | 0.2 | - | 0.020 | - |
| 3 JUL 85 | 08:45 | 6.50 | 13.0 | 2.0 | 20.0 | 11.5 | 319.5 | 2.0 | 1.0 | 0.155 | 0.076 |
| 9 JUL 85 | 01:15 | 6.00 | 128.5 | 21.4 | 96.0 | 19.0 | 339.0 | 80.8 | 67.2 | 0.629 | 0.523 |
| 26 JUL 85 | 09:15 | 6.25 | 44.5 | 7.1 | 62.0 | 0.0 | 105.5 | 23.7 | 12.4 | 0.533 | 0.280 |
| 12 AUG 85 | 19:30 | 42.25 | 69.5 | 1.6 | 36.0 | 16.0 | 32.0 | 14.5 | 8.5 | 0.209 | 0.123 |
| 16 AUG 85 | 02:45 | 3.50 | 26.5 | 7.6 | 28.0 | 98.0 | 121.5 | 4.1 | 2.6 | 0.154 | 0.100 |
| 16 AUG 85 | 11:15 | 4.00 | 40.0 | 9.9 | 34.0 | 124.5 | 148.0 | 19.7 | 15.6 | 0.493 | 0.390 |
| 21 AUG 85 | 16:15 | 17.25 | 74.0 | 4.3 | 74.0 | 101.0 | 206.5 | 39.8 | 34.7 | 0.538 | 0.469 |
| 25 AUG 85 | 20:30 | 20.00 | 142.5 | 7.1 | 62.0 | 146.5 | 312.5 | 52.8 | 45.9 | 0.371 | 0.322 |
| 26 AUG 85 | 22:00 | 21.00 | 71.0 | 3.4 | 26.0 | 257.5 | 426.5 | 32.1 | 23.0 | 0.453 | 0.324 |

Table A3 - Summary of Rainfall and Runoff Data for Two Plots in Chuk Yuen (Sheet 5 of 5)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | CYA | CYB | CYA | CYB |
| 28 AUG 85 | 01:30 | 0.50 | 21.5 | 43.0 | 68.0 | 198.0 | 488.5 | 9.1 | 7.7 | 0.425 | 0.358 |
| 29 AUG 85 | 04:00 | 8.00 | 43.0 | 5.5 | 32.0 | 215.0 | 454.5 | 8.9 | 7.5 | 0.207 | 0.174 |
| 5 SEP 85 | 03:00 | 10.50 | 34.0 | 3.2 | 38.0 | 8.5 | 417.5 | 14.9 | 9.0 | 0.439 | 0.265 |
| 5 SEP 85 | 17:45 | 19.50 | 121.5 | 6.2 | 46.0 | 42.5 | 451.5 | 84.3 | 73.7 | 0.694 | 0.607 |
| 8 SEP 85 | 09:45 | 6.25 | 18.5 | 3.0 | 24.0 | 183.0 | 453.5 | 1.0 | 0.6 | 0.055 | 0.033 |
| 9 SEP 85 | 21:45 | 11.00 | 13.5 | 1.2 | 16.0 | 206.5 | 477.5 | 1.8 | - | 0.131 | - |
| 10 SEP 85 | 06:15 | 2.50 | 8.5 | 3.4 | 16.0 | 206.0 | 454.0 | - | 0.7 | - | 0.082 |
| 10 SEP 85 | 16:30 | 0.75 | 6.5 | 8.7 | 22.0 | 220.0 | 468.0 | 0.3 | 0.5 | 0.051 | 0.077 |
| 21 SEP 85 | 00:15 | 10.75 | 46.5 | 4.3 | 28.0 | 36.0 | 188.5 | 16.1 | 9.7 | 0.346 | 0.209 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Table A4 - Summary of Rainfall and Runoff Data for the Plot in Kohima Barracks (Sheet 1 of 4)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX | 5-day | 15-day | KOH | - | KOH | - |
| 20 JUN 84 | 19:00 | 0.25 | 5.5 | 22.0 | 22.0 | 244.5 | 284.5 | 1.6 | | 0.293 | |
| 21 JUN 84 | 16:15 | 3.00 | 17.5 | 5.8 | 38.0 | 276.5 | 307.0 | 15.0 | | 0.858 | |
| 25 JUN 84 | 05:30 | 10.50 | 59.0 | 5.6 | 44.0 | 116.0 | 339.0 | 59.1 | | 1.002 | |
| 15 AUG 84 | 00:45 | 1.25 | 14.5 | 11.6 | 34.0 | 119.0 | 255.0 | 2.1 | | 0.142 | |
| 16 AUG 84 | 22:15 | 0.50 | 9.5 | 19.0 | 22.0 | 105.0 | 269.5 | 1.1 | | 0.112 | |
| 20 AUG 84 | 10:30 | 6.50 | 17.5 | 2.7 | 20.0 | 26.5 | 200.0 | 3.5 | | 0.197 | |
| 21 AUG 84 | 04:15 | 8.00 | 6.5 | 0.8 | 6.0 | 32.0 | 181.0 | 7.0 | | 1.075 | |
| 31 AUG 84 | 19:00 | 2.75 | 3.5 | 1.3 | 6.0 | 3.0 | 43.5 | 0.0 | | 0.011 | |
| 1 SEP 84 | 04:30 | 26.75 | 101.5 | 3.8 | 30.0 | 5.0 | 37.5 | 60.2 | | 0.593 | |
| 16 SEP 84 | 05:00 | 6.50 | 74.0 | 11.4 | 38.0 | 5.0 | 125.5 | 15.8 | | 0.214 | |
| 19 SEP 84 | 13:00 | 2.00 | 15.0 | 7.5 | 32.0 | 79.5 | 100.5 | 8.3 | | 0.550 | |
| 26 SEP 84 | 01:30 | 2.50 | 31.0 | 12.4 | 34.0 | 3.5 | 138.5 | 11.7 | | 0.376 | |

Table A4 - Summary of Rainfall and Runoff Data for the Plot in Kohima Barracks (Sheet 2 of 4)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX. | 5-day | 15-day | KOH | - | KOH | - |
| 26 SEP 84 | 19:45 | 2.00 | 6.0 | 3.0 | 12.0 | 66.5 | 201.5 | 0.7 | | 0.123 | |
| 10 OCT 84 | 21:45 | 8.75 | 145.0 | 16.6 | 80.0 | 6.0 | 13.5 | 36.1 | | 0.249 | |
| 10 APR 85 | 11:15 | 24.75 | 86.0 | 3.5 | 74.0 | 65.5 | 128.0 | 40.1 | | 0.467 | |
| 19 APR 85 | 23:15 | 4.00 | 30.0 | 7.6 | 20.0 | 8.0 | 214.5 | 8.5 | | 0.283 | |
| 21 MAY 85 | 10:30 | 1.25 | 16.5 | 13.2 | 40.0 | 0.0 | 3.0 | 2.2 | | 0.132 | |
| 28 MAY 85 | 04:30 | 2.75 | 8.5 | 6.8 | 22.0 | 4.5 | 23.5 | 1.1 | | 0.126 | |
| 28 MAY 85 | 12:15 | 4.25 | 20.0 | 5.0 | 14.0 | 13.5 | 32.5 | 9.6 | | 0.481 | |
| 4 JUN 85 | 03:30 | 13.50 | 33.5 | 2.5 | 26.0 | 5.5 | 59.5 | 20.1 | | 0.601 | |
| 24 JUN 85 | 08:30 | 5.00 | 3.5 | 0.7 | 2.0 | 10.0 | 19.0 | 1.6 | | 0.463 | |
| 24 JUN 85 | 17:45 | 34.25 | 276.0 | 8.1 | 88.0 | 13.5 | 22.5 | 245.1 | | 0.888 | |
| 27 JUN 85 | 02:30 | 0.50 | 4.5 | 9.0 | 12.0 | 288.0 | 293.5 | 1.3 | | 0.293 | |
| 29 JUN 85 | 16:15 | 2.50 | 7.0 | 2.8 | 6.0 | 293.5 | 302.0 | 1.1 | | 0.160 | |

Table A4 - Summary of Rainfall and Runoff Data for the Plot in Kohima Barracks (Sheet 3 of 4)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG. | MAX. | 5-day | 15-day | KOH | - | KOH | - |
| 3 JUL 85 | 22:15 | 0.50 | 12.5 | 25.0 | 46.0 | 11.0 | 308.0 | 9.8 | | 0.782 | |
| 8 JUL 85 | 00:15 | 1.25 | 45.0 | 36.0 | 58.0 | 38.0 | 344.5 | 3.4 | | 0.076 | |
| 8 JUL 85 | 15:15 | 2.25 | 7.5 | 3.3 | 10.0 | 83.0 | 389.5 | 1.6 | | 0.215 | |
| 9 JUL 85 | 02:00 | 5.25 | 56.0 | 10.7 | 52.0 | 55.0 | 392.0 | 38.1 | | 0.681 | |
| 18 JUL 85 | 14:00 | 1.75 | 28.5 | 16.3 | 40.0 | 17.0 | 166.0 | 7.1 | | 0.249 | |
| 19 JUL 85 | 02:30 | 0.50 | 4.0 | 8.0 | 14.0 | 46.0 | 158.5 | 1.1 | | 0.277 | |
| 19 JUL 85 | 09:00 | 7.25 | 33.5 | 4.6 | 20.0 | 50.0 | 162.5 | 16.6 | | 0.496 | |
| 20 JUL 85 | 01:15 | 7.25 | 21.5 | 3.0 | 20.0 | 82.5 | 196.0 | 19.2 | | 0.892 | |
| 20 JUL 85 | 19:15 | 0.25 | 2.5 | 10.0 | 10.0 | 104.0 | 217.5 | 0.9 | | 0.340 | |
| 26 JUL 85 | 10:45 | 1.00 | 13.0 | 13.0 | 36.0 | 0.5 | 108.0 | 3.9 | | 0.302 | |
| 26 JUL 85 | 14:15 | 1.25 | 7.5 | 6.0 | 16.0 | 13.5 | 121.5 | 2.3 | | 0.304 | |
| 3 AUG 85 | 04:15 | 2.00 | 7.5 | 3.8 | 16.0 | 0.5 | 85.0 | 0.7 | | 0.089 | |

Table A4 - Summary of Rainfall and Runoff Data for the Plot in Kohima Barracks (Sheet 4 of 4)

| DATE | TIME | RAINFALL DURATION (hr) | RAINFALL AMOUNT RECORDED (mm) | RAINFALL INTENSITY (mm/hr) | | ANTECEDENT RAINFALL (mm) | | RUNOFF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | AMOUNT (mm) | | COEFFICIENT | |
| | | | | AVG | MAX | 5-day | 15-day | KOH | - | KOH | - |
| 8 AUG 85 | 05:40 | 3.00 | 8.5 | 2.8 | 16.0 | 8.5 | 31.5 | 0.8 | | 0.095 | |
| 12 AUG 85 | 03:15 | 3.50 | 15.0 | 4.3 | 20.0 | 11.0 | 22.0 | 2.8 | | 0.185 | |
| 12 AUG 85 | 19:15 | 12.25 | 28.5 | 2.3 | 24.0 | 26.5 | 37.5 | 12.0 | | 0.422 | |
| 13 AUG 85 | 18:00 | 20.00 | 27.5 | 1.4 | 20.0 | 56.5 | 65.5 | 14.8 | | 0.537 | |
| 21 AUG 85 | 19:45 | 14.50 | 91.0 | 6.3 | 28.0 | 140.5 | 233.5 | 82.7 | | 0.908 | |
| 25 AUG 85 | 14:00 | 0.50 | 6.0 | 12.0 | 18.0 | 116.0 | 317.0 | 0.9 | | 0.142 | |
| 25 AUG 85 | 21:45 | 11.50 | 133.5 | 11.6 | 74.0 | 123.0 | 324.0 | 129.6 | | 0.971 | |
| 28 SEP 85 | 23:15 | 8.00 | 23.0 | 2.9 | 16.0 | 4.5 | 29.0 | 6.1 | | 0.264 | |
| 1 OCT 85 | 00:15 | 2.50 | 43.0 | 17.2 | 52.0 | 30.0 | 54.5 | 28.4 | | 0.661 | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

# APPENDIX B

## RELEVANT FORMULAE AND MATHEMATICAL RELATIONS

# APPENDIX B

## CONTENTS

## B.1 Interception

Horton (1919) provided the empirical formula :

$$L = a + b.P^n$$

where L = interception, P = rainfall, and a, b and n are empirical constants for a particular vegetation type.

Kittredge (1948) and Butler (1957) suggested the formula :

$$L = S_i + KEt$$

where $S_i$ = interception storage retained against wind and gravity, K = ratio of intercepting leaves surface area to horizontal projection of the area, E = rate of water evaporation during the rain period and t = time.

Linsley et al (1949) modified the above equation to :

$$L = (K_1 + K_2 \cdot t)(1 - \exp(-P/(K_1 + K_2 \cdot t))$$

where $K_1$ and $K_2$ are equivalent to $S_i$ and KE respectively.

## B.2 Depression Storage

Linsley et al (1949) proposed the following equation :

$$V = S_d\ (1 - \exp\ (-KP_e))$$

where V = depression storage, $S_d$ = maximum depression storage capacity, K = constant equivalent to $1/S_d$ and $P_e$ = rainfall minus interception, infiltration and evaporation. The values of $S_d$ for different soils were discussed in Overton & Meadows (1976).

## B.3 Infiltration

The Green & Ampt (1911) model assumed a distinct and precisely defined wetting front of infiltration descending into the ground during the rainfall period with a suction $H_f$ at the wetting front. Infiltration may be found from the expression :

$$t = \frac{C}{K}\ (\frac{F}{C} - \ln\ (1 + \frac{F}{C}))$$

where t = rainfall duration, C = $\Delta\Theta . \Delta H$, $\Delta\Theta$ = difference between initial soil moisture content and the moisture content in the wet zone above the wetting front, $\Delta H$ = head difference between water head at the surface and the suction $H_f$ at the wetting front, F = total infiltration and K = soil permeability. Further discussion of this approach can be found in Overton & Meadows (1976).

Lumb (1962, 1975) used the wetting band approach and diffusion theory to derive the equation :

$$h = (Dt)^{0.5} + \frac{Kt}{n(S_f - S_o)}$$

which may be simplified to :

$$h = \frac{Kt}{n\ (S_f - S_o)}$$

where h = depth of wetting front, D = diffusion parameter, K = soil permeability, n = porosity, $S_o$ and $S_f$ = initial and final degrees of saturation respectively and $t^o$= rainfall duration.

Horton (1939) proposed the infiltration equation :

$$f = f_c + (f_o - f_c)\ \exp\ (-ct)$$

where f = infiltration rate after an elapsed time t, $f_o$ and $f_c$ = initial and final infiltration rates respectively and c = infiltration constant which is a function of soil and vegetation types.

Holtan (1961) proposed an infiltration formula, on the basis of substantial field experiments, as follows :

$$f = a\ F_p^{\ n} + f_c$$

where f = infiltration rate, $F_p$ = remaining soil water storage capacity, $f_c$ = final rate of infiltration, and a and n are empirical constants.

Phillip (1960) developed a simple formula on the basis of diffusion theory as follows :

$$f = \tfrac{1}{2}At^{-0.5} + B$$

where f = infiltration rate at an elapsed time t, and A and B are constants related to soil properties and soil water movement characteristics.

## B.4 SCS Curve Number Method

The Soil Conservation Service (SCS, 1972) of the US Department of Agriculture developed a semi-empirical method for the estimation of runoff from various types of catchment area. The basic assumption is that the following equation can be applied to all runoff situations :

$$\frac{P - Q - I_a}{S} = \frac{Q}{P - I_a}$$

where P = storm rainfall, Q = runoff, $I_a$ = initial abstraction and S = the potential maximum retention at the start of the storm.

Runoff can be estimated from

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

In the general condition the initial abstraction is assumed to be 20% of the maximum retention :

$$I_a = 0.2S$$

therefore :

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

This method relies on a series of runoff curves (Figure 7) with different curve numbers. The curve number CN is related to the maximum retention S as follows :

$$S = 25.4 \left(\frac{1000}{CN} - 10\right)$$

where S is in the unit of mm.

SCS (1972) estimated CN for various types of soil, surface cover and land use, and antecedent rainfall conditions. Some of the listings are provided in Tables B.1 to B.5.

## B.5 Calculation of Flow from Hydrograph

The theoretical equation to calculate flow rate through a weir is :

$$Q = \frac{8}{15} \sqrt{2g} \tan \frac{\theta}{2} h^{2.50}$$

or

$$Q = K (\theta) h^{2.50}$$

where Q = flow rate, g = gravitational constant, $\theta$ = angle of the V-notch and h is water head above the bottom of the V-notch (stage).

The actual relation from wier calibration may take the form :

$$Q = Kh^n$$

where K and n are constants determined from the calibration of the particular weir. They may be obtained from a log-log plot of measured Q and h.

The calculation of runoff volume was made by digitizing the hydrograph into a series of coordinates (time, stage). These are the coordinates of points which, when joined together by short straight lines, will approximate the hydrograph very closely. The number of points for each hydrograph varied from six to 140 depending on the complexity of the hydrograph. The runoff is the integration of the flow volumes under the straight line segments. The flow volume under each segment, which has a slope gradient of $\Delta h/\Delta t$, is given by :

$$V = \frac{K}{(n+1)} \cdot \frac{\Delta t}{\Delta h} \cdot (h_2^{n+1} - h_1^{n+1})$$

For a segment with $h_1 = h_2$ ($\Delta h = 0$), the following equation was used :

$$V = Kh^n \cdot \Delta t$$

where V is the volume of the runoff through the weir, $\Delta t = t_2 - t_1$ and $\Delta h = h_2 - h_1$. $h_i$ and $t_i$ are coordinates of the hydrograph which were entered into the computer for the calculation.

## B.6 Modified Ø-Index Runoff Model

The Ø-index method assumes a sudden change from no runoff at rainfall intensity less than the critical value, to full runoff for rainfall in excess of the critical value. A more gradual change was attempted in this study. Runoff would be dependent on rain intensity; at very low values there is no runoff, at intermediate values part of the rain will be runoff, and at high values all rainfall greater than a critical intensity (equivalent to the Ø-index) will be runoff.

The runoff therefore is expressed as :

$$Q = R\,(P_m - I_a) + (P - P_m)$$

where Q = runoff, R = ratio of runoff over rainfall for intermediate intensity, $P_m$ = the part of rainfall below the critical intensity $i_c$, $I_a$ = initial abstraction and P = total storm rainfall.

This can be expressed in terms of storm loss :

$$L = P - Q = (1 - R)\,P_m + R.I_a$$

A linear regression analysis between L and $P_m$ will achieve the coefficients (1 - R) and $R.I_a$, and R and $I_a$ can then be calculated. In the calculation, a range of critical intensity values was used and the one which gave the highest correlation coefficient between L and $P_m$ was adopted. Actual 15-minute rainfall data were used in the calculation. The rainstorms having maximum intensity less than $i_c$ were excluded from the analysis. In the trial, $i_c$ was increased from low to high values, and the number of events included was correspondingly decreased. It was found that the correlation coefficient was increasing, and the first peak was taken as the maximum when the coefficient started to decrease. The higher range of $i_c$ was not investigated, since this would have involved a much smaller number of events. A fixed increment of 1.0 mm/hr. was used in all analyses.

# APPENDIX B

## LIST OF TABLES

Table B1 – Runoff Curve Numbers for Hydrologic Soil-Cover Complexes

| Cover | | | Hydrologic Soil Group | | | |
|---|---|---|---|---|---|---|
| Land Use | Treatment or Practice | Hydrologic Condition | A | B | C | D |
| Fallow | Straight row | - | 77 | 86 | 91 | 94 |
| Row Crops | Straight row | Poor | 72 | 81 | 88 | 91 |
| | Straight row | Good | 67 | 78 | 85 | 89 |
| | Contoured | Poor | 70 | 79 | 84 | 88 |
| | Contoured | Good | 65 | 75 | 82 | 86 |
| | Contoured and terraced | Poor | 66 | 74 | 80 | 82 |
| | Contoured and terraced | Good | 62 | 71 | 78 | 81 |
| Small Grain | Straight row | Poor | 65 | 76 | 84 | 88 |
| | | Good | 63 | 75 | 83 | 87 |
| | Contoured | Poor | 63 | 74 | 82 | 85 |
| | | Good | 61 | 73 | 81 | 84 |
| | Contoured and terraced | Poor | 61 | 72 | 79 | 82 |
| | | Good | 59 | 70 | 78 | 81 |
| Close-seeded Legumes or Rotation Meadow | Straight row | Poor | 66 | 77 | 85 | 89 |
| | Straight row | Good | 58 | 72 | 81 | 85 |
| | Contoured | Poor | 64 | 75 | 83 | 85 |
| | Contoured | Good | 55 | 69 | 78 | 83 |
| | Contoured and terraced | Poor | 63 | 73 | 80 | 83 |
| | Contoured and terraced | Good | 51 | 67 | 76 | 80 |
| Pasture or Range | | Poor | 68 | 79 | 86 | 89 |
| | | Fair | 49 | 69 | 79 | 84 |
| | | Good | 39 | 61 | 74 | 80 |
| | Contoured | Poor | 47 | 67 | 81 | 88 |
| | Contoured | Fair | 25 | 59 | 75 | 83 |
| | Contoured | Good | 6 | 35 | 70 | 79 |
| Meadow | | Good | 30 | 58 | 71 | 78 |
| Woods | | Poor | 45 | 66 | 77 | 83 |
| | | Fair | 36 | 60 | 73 | 79 |
| | | Good | 25 | 55 | 70 | 77 |
| Farmsteads | | - | 59 | 74 | 82 | 86 |
| Roads (Dirt) | | - | 72 | 82 | 87 | 89 |
| (Hard Surface) | | - | 74 | 84 | 90 | 92 |

Table B2 - Hydrologic Soil Group

| Soil Group | Description |
|---|---|
| A | Lowest runoff potential: Includes deep sands with very little silt and clay, also deep, rapidly permeable loess. |
| B | Moderately low runoff potential: Mostly sandy soils less deep than A, and loess less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting. |
| C | Moderately low runoff potential: Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D. The group has below-average infiltration after presaturation. |
| D | Highest runoff potential: Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface. |

Table B3 - Runoff Curve Numbers for Urban Areas

| Zoning Classification | Percent Imperviousness | Curve Numbers by Antecedent Moisture Conditions | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | II | | | | III | | | |
| | | Hydrologic Soil Groups | | | | Hydrologic Soil Groups | | | |
| | | A | B | C | D | A | B | C | D |
| Business, Industrial, or Commercial | 75 | 82 | 88 | 90 | 91 | 92 | 95 | 96 | 97 |
| Apartment House | 65 | 78 | 85 | 88 | 90 | 90 | 94 | 95 | 96 |
| Schools | 45 | 68 | 78 | 84 | 87 | 84 | 90 | 93 | 95 |
| Urban Residential | 40 | 65 | 77 | 83 | 86 | 82 | 89 | 93 | 94 |
| Parks and Cemeteries | 20 | 55 | 71 | 79 | 83 | 74 | 86 | 91 | 93 |
| Unimproved Areas | 15 | 53 | 70 | 78 | 82 | 73 | 85 | 90 | 92 |
| Lawns | 0 | 45 | 65 | 75 | 80 | 66 | 82 | 88 | 91 |

Table B4 - Definition of Antecedent Moisture Conditions

| Class | 5-day Total Antecedent Rainfall (mm) | |
|---|---|---|
| | Dormant Season | Growing Season |
| I | < 12.7 | < 35.6 |
| II | 12.7 - 27.9 | 35.6 - 53.3 |
| III | > 27.9 | > 53.3 |

Table B5 - Relationships between CN and AMC Classes

| Antecedent Moisture Class | | |
|---|---|---|
| I | II | III |
| 100 | 100 | 100 |
| 87 | 95 | 98 |
| 78 | 90 | 96 |
| 70 | 85 | 94 |
| 63 | 80 | 91 |
| 57 | 75 | 88 |
| 51 | 70 | 85 |
| 45 | 65 | 82 |
| 40 | 60 | 78 |
| 35 | 55 | 74 |
| 31 | 50 | 70 |
| 22 | 40 | 60 |
| 15 | 30 | 50 |
| 9 | 20 | 37 |
| 4 | 10 | 22 |
| 0 | 0 | 0 |

# APPENDIX C

## CALIBRATION OF WEIRS

## APPENDIX C : CALIBRATION OF WEIRS

For basic calculation of flow from V-notch weirs, the theoretical equation in Appendix B.5 may be used if a high degree of accuracy is not required. However, for the more accurate results required for more detailed correlation studies such as in this project, weirs must be calibrated under actual field conditions. The actual weir constant may differ significantly from the theoretical value due to inaccuracies in the cutting of the V-notch into the thin plate, as well as in the dimensions of the stilling basin. A comprehensive discussion on the proper use of weirs in flow measurement and further specialized references can be found in Ackers et al (1978).

It should be noted that there seems to be little reference to weir calibration in previous related studies in Hong Kong. In the Mid-Levels Study Report (GCO, 1982a; Halcrow, 1980) there is no reference to the use of a stilling basin to regulate water flow before it reached the weir. Calibration of concrete weirs was carried out at six locations out of the total of thirteen locations. Hsu et al (1983) used a small cylindrical tank with a $2.1^{o}$ V-notch slot, and there is no reference to calibration in their report.

Weir calibration was carried out for the four weirs used in this study. A receptable of known volume was used to measure the volume of flow and a stop watch was used to record the elapsed time, see Plate 8. Height of water was measured with the float-recorder system used for the actual runoff measurements. The calibration was made on site, using water from nearby fire hydrants, and the test was repeated if deemed necessary. The test was carried out at various heights of water, and covered the full range of the weir capacity.

The results from individual measurements are plotted in log-log form in Figure C1 for all of the four weirs. The best-fit lines are also shown in the figure. The slopes of these lines could have been slightly different, but they were kept the same (without significant error) because it simplified the calculation procedures. The four calibration curves are plotted together in Figure C2 in comparison with the theoretical curves. Note that the gradient of these calibrated curves is 2.20, in contrast to the theoretical value of 2.50. This is thought due to the dimensions and arrangement of the stilling basins, which are the same at all sites (Ackers et al, 1978). The weir constants used in the runoff calculation are shown in Table 5. The calibration by Halcrow (1980) gave exponential values of 2.31 to 2.37 for four of the weirs, and 2.65 to 2.67 for the other two weirs. Their calibration covered only parts of the total weir capacity, however.

# APPENDIX C

## LIST OF FIGURES

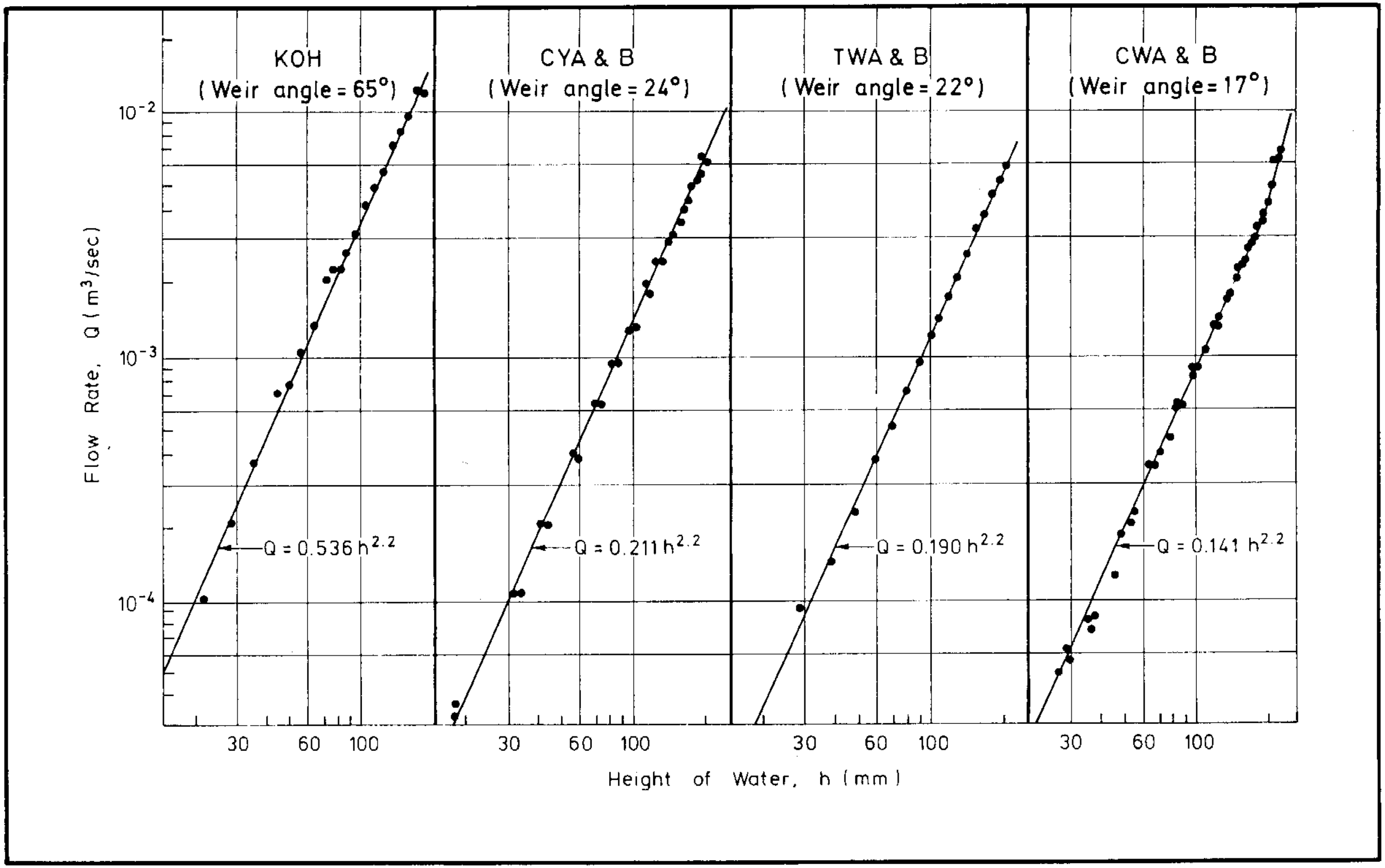



Figure C1 – Flow Rates at Various Stages from Calibration at the Four Weirs

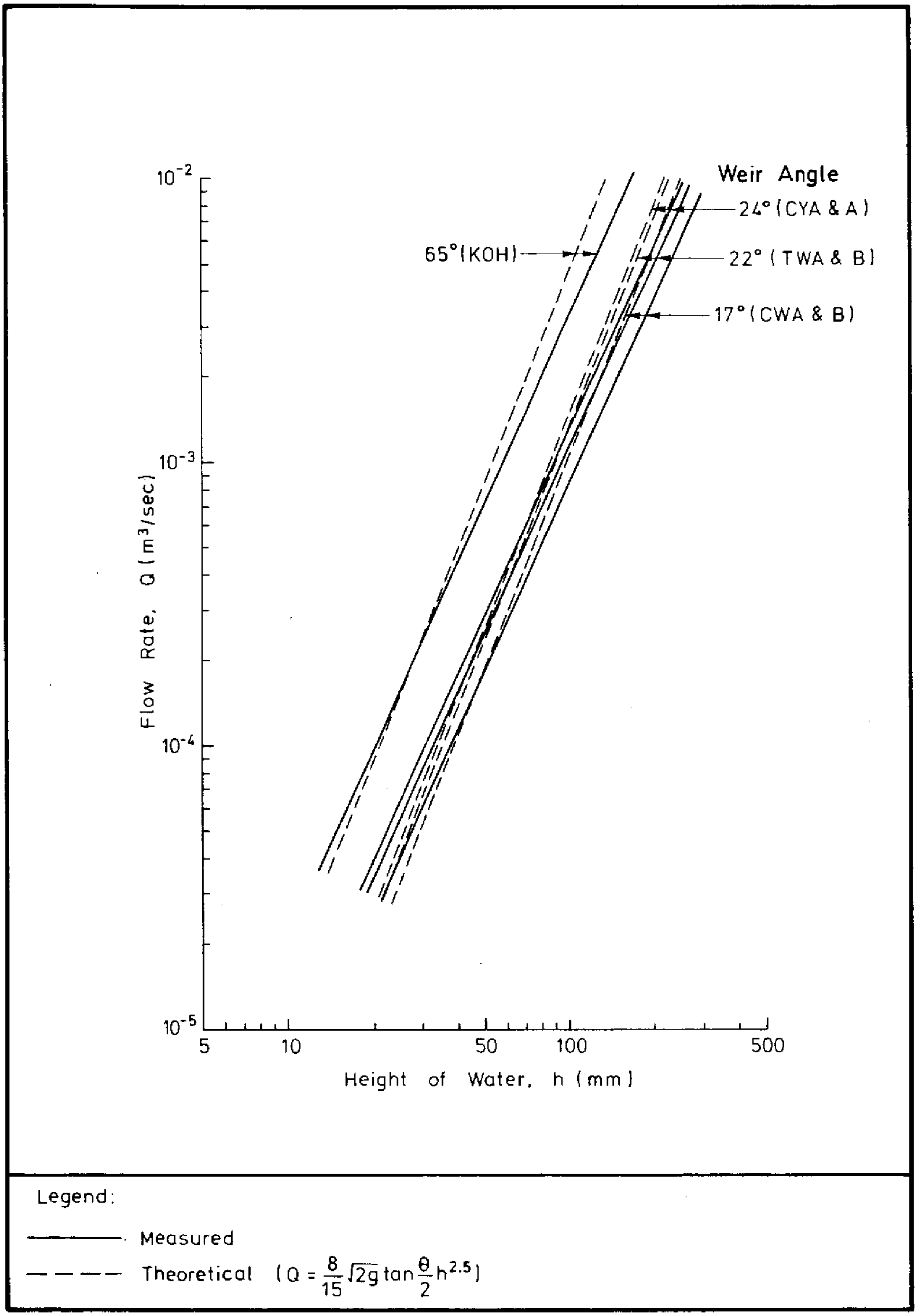



Figure C2 - Weir Calibration Curves in Comparison with Theoretical Curves