CORRELATION BETWEEN RAINFALL AND NATURAL TERRAIN LANDSLIDE OCCURRENCE IN HONG KONG

GEO REPORT No. 168

F.W.Y. Ko

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

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Prepared by:

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

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PREFACE

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R.K.S. Chan
Head, Geotechnical Engineering Office
September 2005

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FOREWORD

Assessing the correlation between rainfall and natural terrain landslide occurrence is essential to improving understanding of natural terrain landslide hazards and effectively managing their risk. However, the assessment involves two major technical difficulties. Firstly, there are a large amount of spatial data to collate and analyse. Secondly, despite of the large volume of data available, they provide limited information on the exact date and time of natural terrain landslide occurrence.

This study has overcome the technical difficulties, and derived rainfall-natural terrain landslide correlations for natural terrain in Hong Kong based on rigorous spatial analysis of rainfall and natural terrain landslide data from 1985 to 2000. The buildup of Geographic Information System (GIS) capability in the Geotechnical Engineering Office over the years has made it possible now for the required data collation and analysis work to be efficiently and effectively implemented on a GIS platform. Application of statistical techniques has helped to resolve the constraint in respect of lack of information on the timing of natural terrain landslide occurrence.

This study was carried out by Ms Florence W. Y. Ko under the direct supervision of Mr H. N. Wong. Ms L. Y. Pau took part in the GIS work. Mr W. K. Ho assisted in the GIS data collation and analysis.

(H.N. Wong)
Chief Geotechnical Engineer/Planning

ABSTRACT

A preliminary assessment of the relationship between rainfall and natural terrain landslide occurrence in Hong Kong was carried out by Evans (1997). From the assessment, a plot of cumulative percentage of natural terrain landslides against maximum rolling 24-hour rainfall, based on manual extraction of data from 1985 to 1994, was derived. The assessment was updated in this study using data from 1985 to 2000. Geographic Information System (GIS) and geostatistical techniques were applied, which improve the accuracy of the cumulative plot. However, the plot only gives a causal relationship between the historical natural terrain landslides and the maximum rolling 24-hour rainfall at the landslide locations in the year of landsliding. It is not a rigorous rainfall-natural terrain landslide analysis, and its application to identifying rainfall thresholds and estimating the potential number of natural terrain landslides for a given rainfall condition could be misleading.

To overcome the limitations of the cumulative plot, a detailed assessment was carried out for establishing the rainfall-natural terrain landslide correlation in Hong Kong. The assessment incorporated the methodology that has been applied over the years in deriving rainfall-landslide correlation for man-made slopes in Hong Kong, together with the use of GIS technology and statistical models to further improve the assessment. In the correlation, maximum rolling 24-hour rainfall normalized by location-specific mean annual rainfall was adopted, to give a better representation of the severity of the rainfall conditions at different locations.

Based on spatial analysis of rainfall-natural terrain landslide data from 1985 to 2000, a year-based rainfall-natural terrain landslide correlation was established. Then, the year-based correlation was transformed statistically into a storm-based correlation. The storm-based correlation was tested by comparing the predicted number of natural terrain landslides with the actual number of natural terrain landslides from 1985 to 2000, and was found to be reliable. The correlation enables the assessment of the probability of occurrence of different natural terrain landslide densities under different rainfall scenarios, and is applicable to hazard identification, risk quantification and formulation of natural terrain landslide warning system.

For terrain subject to comparable rainfall intensity, a notable correlation of natural terrain landslide density with terrain susceptibility classes was observed. The year-based correlation has been further developed into correlations that apply to different susceptibility classes. Further work is at hand to improve the terrain susceptibility classification, based on which the rainfall-landslide correlation can be enhanced. Other areas of further work were also identified.

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1. INTRODUCTION

The objective of this study is to assess the correlation between rainfall and natural terrain landslide occurrence in Hong Kong.

The following two key areas of work were carried out:

(a) the plots of cumulative percentage of natural terrain landslides against rainfall prepared by Evans (1997) were updated and the findings were reviewed; and

(b) the correlation between rainfall and natural terrain landslide occurrence was assessed using a statistically rigorous methodology.

2. DATA AND ASSUMPTIONS

The study was based on the available data on natural terrain landslides and rainfall between 1985 and 2000. 'Natural terrain' refers to terrain that has not been modified substantially by human activity, but includes areas where grazing, hill fires and deforestation may have occurred (Ng et al, 2002). In compiling the Natural Terrain Landslide Inventory (NTLI) (King, 1999), development lines that broadly define the boundaries between natural hillsides and developed areas were identified. The natural hillsides delineated by these development lines were taken as natural terrain in identifying natural terrain landslides for inclusion into the NTLI.

In this study, natural terrain landslide data recorded in the NTLI were adopted. Aerial photographs with good spatial and temporal coverage are available between 1985 and 2000. Hence, the natural terrain landslides recorded in the NTLI over this period are sufficiently comprehensive and the year of initiation of each of the natural terrain landslides can be reliably determined.

Comprehensive rainfall data recorded at five-minute intervals by Geotechncial Engineering Office (GEO)'s automatic raingauges are available since 1985. These were used in this study, which covers the period 1985 to 2000. Based on the rainfall data, the maximum rolling 24-hour rainfall at the location of each natural terrain landslide in the year of its occurrence was determined.

Maximum rolling 24-hour rainfall was adopted in this study in assessing rainfall-natural terrain landslide correlation. Maximum rolling 24-hour rainfall has also been adopted by the GEO in establishing the correlation with landslides in man-made slope features (Yu, 2002). The current landslide warning criteria, which principally covers landslides in man-made slope features, is based on the use of maximum rolling 24-hour rainfall (Pun et al, 1999; Chan et al, 2003).

It should be noted that only the year-based maximum rolling 24-hour rainfall can be readily determined for natural terrain landslides, and not the storm-based maximum rolling 24-hour rainfall. This is due to the fact that only the year of natural terrain landslide occurrence could be ascertained. For most of the natural terrain landslides, the exact date and time of occurrence is not known.

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3. CUMULATIVE PLOTS OF NATURAL TERRAIN LANDSLIDES AGAINST RAINFALL

3.1 Previous Work Carried Out

A preliminary assessment of the relationship between rainfall and natural terrain landslide initiation in the period from 1985 to 1994 was carried out by Evans (1997). The method adopted is summarized in Appendix A. In the assessment, rainfall data were extracted manually from printed isohyets of rolling 24-hour rainfall for selected rainstorm events. Based on these, the maximum rolling 24-hour rainfall in the year of occurrence was determined for each natural terrain landslide. Then the rainfall was divided by the mean annual rainfall at the location of the natural terrain landslide to obtain the normalized maximum rolling 24-hour rainfall that corresponds to the natural terrain landslide. Evans (1997) prepared plots of cumulative percentage of natural terrain landslides against the maximum rolling 24-hour rainfall (Figure 1) and against the normalized maximum rolling 24-hour rainfall (Figure 2). Three points of abrupt change in the gradient of the normalized rainfall cumulative plot were noticed. These were taken as rainfall thresholds where significant increase in the number of natural terrain landslides would occur (Figure 2).

3.2 Update

The cumulative plots were updated in this study with the following improvements made:

(a) The study period was extended to 2000. This amounts to about 75% increase in the number of natural terrain landslides.

(b) For consistency, natural terrain delineated by the 2000 development lines were considered. The total area is about 659 km^2.

(c) Geostatistical analyses were carried out using the available GEO automatic raingauge data to construct rainfall isohyets and derive maximum rolling 24-hour rainfall data.

(d) Data processing and analysis were carried out in GEO's Geographic Information System (GIS). This has enhanced efficiency, minimized human error and improved accuracy.

Details of the work carried out are described in Appendix B.

Figures 3 and 4 show the updated plots of cumulative percentage of natural terrain landslides against absolute and normalized maximum rolling 24-hour rainfall, respectively.

3.3 Diagnosis

For comparison purposes, plots of cumulative percentage of natural terrain landslides against normalized maximum rolling 24-hour rainfall for selected rainstorms have also been prepared. These are shown in Figure 5, together with the plot for the period 1985 to 2000

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derived from this study (i.e. that shown in Figure 4) and the plot obtained by Evans (1997) for the period 1985 to 1994 (i.e. that shown in Figure 2). The updated plots given in Figures 3 and 4 are closer presentation of the rainfall-natural terrain landslide relationship because they are derived from more comprehensive data and improved analysis. However, as shown in Figure 5, the significant difference among the various plots is notable. In interpreting and applying the plots, consideration should be given to the following:

(a) The plots are merely a factual, graphical representation of the cumulative percentage of historical natural terrain landslide locations subject to different year-based maximum rolling 24-hour rainfalls. While the plots give some indication of the relationship between the historical rainfall and natural terrain landslide data, they do not form a rigorous rainfall-natural terrain landslide correlation. The data included in the plots come from locations where historical natural terrain landslides have occurred. However, in producing the plots, no consideration was given to locations where natural terrain landslides have not occurred and to their rainfall conditions.

(b) Since only the year and not the date and time of natural terrain landslide occurrence is certain, the actual rolling 24-hour rainfall that corresponds to natural terrain landslide initiation is not known. This actual rolling 24-hour rainfall is less than the maximum rolling 24-hour rainfall at the natural terrain landslide location in its year of occurrence. Hence, the plots of cumulative percentage of natural terrain landslides against year-based maximum rolling 24-hour rainfall (irrespective of whether normalization is carried out or not), instead of being the curve that defines the rainfall-natural terrain landslide relationship, is the lower boundary of the zone within which such relationship may fall. Any interpretation that is based on the shape of the curve, such as points of abrupt change in gradient, may be unrealistic.

(c) In addition, it should be noted that the position of top end of the cumulative plot, which corresponds to 100% natural terrain landslide occurrence, is controlled by the maximum rainfall that has occurred at the natural terrain landslide locations over the whole period. The longer the observation period, the greater will be the chance that this ‘maximum rainfall’ is higher. The plot derived from a long observation period would tend to be flatter, and that from a short observation period steeper. This further illustrates that the plots are not representing an intrinsic, unique rainfall-natural terrain landslide relationship.

(d) Given the above constraints, the plots are of limited use in assessment of rainfall-natural terrain landslide correlation and in related work, such as establishment of landslide warning criteria. The rainfall thresholds identified by Evans (1997), as shown in Figures 2 and 5, are probably artifacts associated with the nature of the plots, data accuracy and methodology adopted in producing the plots. The potential number of natural terrain landslides calculated with reference to these rainfall thresholds for use in the Landslide Potential Indices (Evans et al, 2002) could be misleading.

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4. CORRELATION BETWEEN RAINFALL AND NATURAL TERRAIN LANDSLIDE OCCURRENCE

4.1 Methodology

A rigorous assessment of rainfall-natural terrain landslide correlation was carried out, which overcomes the deficiencies of the cumulative plots described in Section 3 above. The assessment has incorporated the methodology that has been applied over the years in establishing rainfall-landslide correlation for man-made slope features in Hong Kong (Yu, 2002; Pun et al, 2003), together with the use of GIS spatial analysis and geostatistical techniques to further improve the assessment.

Details of the assessment are explained in Appendix C. The following are the main steps of work on deriving the year-based rainfall-natural terrain landslide correlation:

(a) Extract from the NTLI natural terrain landslides between 1985 and 2000 in relation to the natural terrain delineated by the 2000 development lines (Figure 6).

(b) Identify the normalized maximum rolling 24-hour rainfall for each natural terrain landslide based on its year of occurrence and location.

(c) Group the normalized maximum rolling 24-hour rainfall into different ranges of rainfall intensity: 0.00-0.05, >0.05-0.10, >0.10-0.15, >0.15-0.20, >0.20-0.25, >0.25-0.30, >0.30-0.35.

(d) Count for each range of rainfall intensity the total number of natural terrain landslides and the total year-based area of natural terrain affected (km^2) between 1985 and 2000.

(e) Calculate for each range of rainfall intensity the year-based natural terrain landslide density ($no./km^2$).

The work was undertaken on GEO's GIS platform.

4.2 Findings

The year-based correlation between normalized maximum rolling 24-hour rainfall and natural terrain landslide density is shown in Figure 7. The natural terrain landslide density increases exponentially with the normalized maximum rolling 24-hour rainfall, which is reasonable. While the correlation is statistically rigorous, it should be noted that at the highest rainfall intensity range of >0.30 to 0.35, the total natural terrain area involved over the 16-year observation period is only about 46 km^2 (Appendix C). This amounts to less than 10% of the natural terrain area in Hong Kong. Hence, the natural terrain landslide density calculated for this rainfall intensity range may involve a relatively greater degree of uncertainty.

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4.3 Conversion of Year-based to Storm-based Correlation

The year-based correlation, though rigorously established, is difficult to apply. It can be used to estimate the number of natural terrain landslides that would occur when the natural terrain is subject to a given maximum rolling 24-hour rainfall recorded in a year. However, since the correlation is year-based and not storm-based, it cannot be used to estimate the number of natural terrain landslides when the natural terrain is subject to a rainstorm. Since the natural terrain could be hit by many rainstorms in one year, a casual application of this year-based correlation to a rainstorm event would over-estimate the theoretical number of natural terrain landslides in the rainstorm. In practice, rainfall-natural terrain landslide correlation, e.g. in case of formulating and implementing landslide warning criteria, is mostly applied to rainstorm events. Also, where there is a need to assess the probability of natural terrain landslide occurrence using rainfall-natural terrain landslide correlation, a storm-based correlation would have to be used to enable calculation of natural terrain landslide probability based on consideration of rainfall return period. Hence, development of a storm-based correlation between rainfall and natural terrain landslides is essential, particular for advanced rainfall-landslide assessments and related applications.

Since the date and time of the vast majority of the historical natural terrain landslides are not known, limited storm-based historical natural terrain landslide data are available. Therefore, a storm-based rainfall-natural terrain landslide correlation cannot be reliably established using a rigorous spatial analysis as adopted in this study in deriving the year-based correlation.

It is, however, possible to convert the year-based correlation to a storm-based correlation using statistical method. This is due to the fact that the year-based correlation is statistically related to the storm-based correlation. The ranges of maximum rolling 24-hour rainfall intensity can be treated as rainfall scenarios that correspond to different return periods - each with a probability of occurrence that can be calculated with the use of a suitable statistical model. Then, the theoretical frequency of occurrence of each of the rainfall scenarios, as well as the equivalent area of natural terrain affected in one year, can be assessed statistically. As the year-based correlation is the summation of the application of the storm-based correlation to all the rainfall scenarios that would theoretically occur in a year, the storm-based correlation can therefore be derived statistically from the year-based correlation through the use of a relevant statistical model.

Based on this approach, a conversion of the year-based correlation to a storm-based correlation was carried out in this study. Details of the conversion are given in Appendix D. In the conversion, the Poisson statistical model was adopted. Six rainfall scenarios R1 to R6 corresponding to the following ranges of normalized maximum rolling 24-hour rainfall were considered: 0.00 to 0.10; >0.10 to 0.15; >0.15 to 0.20; >0.20 to 0.25; >0.25 to 0.30 and >0.30 to 0.35.

4.4 Results and Reliability of Conversion to Storm-based Correlation

The results of the conversion, i.e. the storm-based natural terrain landslide densities for different rainfall scenarios, are shown in Figure 8, on which the year-based correlation is also given for comparison. At low rainfall intensity, the storm-based natural terrain landslide

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density is much lower than the year-based natural terrain landslide density. This reflects the fact that there is a considerable probability that a low-intensity rainfall scenario may occur more than once in a year at a particular location. At high rainfall intensity, the storm-based natural terrain landslide density is still lower than the year-based one. However, their difference is not very significant because the probability that a high-intensity (hence long return period) rainfall scenario may occur more than once in a year is small. At high rainfall intensity, the reduction in natural terrain landslide density from the year-based correlation to the storm-based correlation is principally the result of the exclusion of some natural terrain landslides that would theoretically have occurred due to the probability that part of the natural terrain may be hit in the year by other rainfall scenarios with a lower rainfall intensity.

The conversion of the year-based correlation to the storm-based correlation using a statistical method could result in inaccuracy, if the historical rainfall occurrence is inconsistent with the statistical model adopted. In order to examine whether or not this may be a serious problem in the conversion carried out in this study, the derived storm-based rainfall-natural terrain landslide correlation has been applied to calculate the theoretical number of natural terrain landslides in the period 1985 to 2000, for comparison with the actual number of natural terrain landslides occurred in the period. The results are shown in Table 1. The following are observed:

(a) The theoretical annual number of natural terrain landslides is calculated to be 302, which matches very well with the actual number of 329. This shows that the statistical model is a realistic representation of the rainfall characteristics and the storm-based rainfall-natural terrain landslide correlation is accurately reflecting the overall level of natural terrain landslide activity from 1985 to 2000. Hence, inaccuracy arising from the application of the statistical method is insignificant and the storm-based rainfall-natural terrain landslide correlation derived is sufficiently reliable.

(b) By establishing the storm-based correlation, the probabilities of occurrence of different landslide densities that correspond to different rainfall scenarios can be assessed. The correlation shows that most of the natural terrain landslides would be triggered by rainfall scenarios R2 to R5, i.e. with normalized maximum rolling 24-hour rainfall from >0.10 to 0.30. For rainfall scenario R1, even though the frequency of occurrence is higher, the relatively lighter rainfall intensity would result in a low natural terrain landslide density and hence the theoretical annual number of natural terrain landslides that would be triggered by this rainfall scenario is less than that by R2 to R5. For rainfall scenario R6, although the natural terrain landslide density is high, its frequency of occurrence is very low and hence the annual number of natural terrain landslides due to R6 is less than that due to R2 to R5. This illustrates the merits of the storm-based correlation for use in hazard identification and quantification of the frequency of rainfall and the number of natural terrain landslides.

(c) The storm-based correlation includes a residual annual probability of 0.002 that an ‘extreme’ rainfall scenario (normalized maximum rolling 24-hour rainfall exceeding 0.35) would occur. Since few historical rainfall-natural terrain landslide data are available over the study period from 1985 to 2000 on this extreme rainfall scenario, its rainfall-natural terrain landslide correlation has not

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been assessed from the statistical conversion of the year-based correlation to storm-based correlation. By extrapolation, the landslide density for this extreme rainfall scenario could be estimated (Figure 9) but the possible degree of uncertainty should not be overlooked.

5. DISCUSSION

Rainfall and natural terrain landslide data from 1985 to 2000 have been examined, and their correlation established. The following deserve attention, particularly in interpreting the findings of the study, applying the rainfall-natural terrain landslide correlation and undertaking further work on the subject:

(a) Correlations derived in this study

The plots of cumulative percentage of natural terrain landslides against rainfall should not be applied as rigorous rainfall-natural terrain landslide correlation. The year-based correlation is derived from the rigorous spatial analysis of the rainfall-natural terrain landslide data. The storm-based correlation, which was converted from the year-based correlation using the statistical method, is reliable and useful for application.

(b) Reliability of correlation

Despite the fact that the exact date and time of occurrence of the natural terrain landslides is not known, the rainfall-natural terrain landslide correlation is representative in that it is rigorously based on the actual number of natural terrain landslides occurred on natural terrain subject to different rainfall intensities. It should be noted that the natural terrain landslides might not necessarily have occurred at the time that the rolling 24-hour rainfall reached its maximum value. Hence, although the correlation can correctly assess the theoretical number of natural terrain landslides that would occur as a result of a rainfall event, it may over-estimate the rainfall that triggered the natural terrain landslides. This should however not be a very serious problem, in view that natural terrain landslides were mostly triggered by severe rainfall and that the correlation is not intended for use in accurate determination of natural terrain landslide-triggering rainfall intensities.

(c) Effects of terrain attributes

The correlation derived from this study covers all natural terrain in Hong Kong. Hence, it is an overall correlation that gives the average natural terrain landslide densities corresponding to different rainfall intensities for the natural hillside, without consideration of other relevant terrain attributes such as gradient, geology, etc. Possible effects of the terrain attributes on natural terrain landslide density can be illustrated by an examination of the spatial distribution of the natural terrain landslides on natural terrain subject to comparable rainfall intensity. For example, Figure 10 shows the natural terrain landslides and normalized maximum rolling 24-hour rainfall in 2000. The vast majority of the natural terrain

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landslides are concentrated in the Northwest New Territories, which demonstrates a strong correlation with the severity of the rainfall conditions. Two locations each with comparable rainfall intensity, one high and the other low, are enlarged in Figure 11, on which the terrain susceptibility classes by Evans & King (1998) are also shown. It can be seen that at low rainfall intensity, the natural terrain landslides occurred only at 'High' and 'Very High' terrain susceptible classes. At high rainfall intensity, natural terrain landslides occurred at all terrain susceptibility classes, including the 'Low' and 'Moderate' susceptibility classes. The 1993 data are shown in Figures 12 and 13, in which this notable relationship of natural terrain landslide occurrence with landslide susceptibility classes is also evident. This relationship brings out the importance of the consideration of terrain susceptibility in assessing rainfall-natural terrain landslide correlation.

(d) Correlation incorporating terrain landslide susceptibility classification

The HKSAR-wide terrain susceptibility classification of Evans & King (1998) was carried out in the early years of GEO's study on natural terrain hazards. Further terrain susceptibility analyses at regional and site-specific scales have been carried out in recent years with the use of improved techniques and additional terrain attributes, as described in Wong (2003). As a preliminary assessment of the effects of the consideration of terrain susceptibility on rainfall-natural terrain landslide correlation, the year-based correlation has been further developed into correlations that apply to terrain with different susceptibility classes (Figure 14). The differentiation in natural terrain landslide densities with respect to terrain susceptibility classes is prominent in all ranges of rainfall intensity. This confirms the importance, as well as the practicality, of the establishment of a rainfall-natural terrain landslide correlation that incorporates terrain susceptibility classification. The HKSAR-wide terrain susceptibility classification is being improved by the GEO. When the improved classification is available, these should be adopted to update the preliminary assessment made in Figure 14. Furthermore, the possibility of carrying out coupled-analysis of terrain susceptibility and rainfall-natural terrain landslide correlation would deserve consideration.

(e) Orographic effects

Orographic effects on rainfall intensity could be significant in Hong Kong (Evans, 1996). Few of GEO's current network of automatic raingauges are placed on highlands. In this study, geostatistical method was applied to construct rainfall isohyets based on projection from the available raingauge data. However, there is still a possibility that the isohyets constructed might not fully reflect the orographic effects and thereby might lead to inaccurate assessment of rainfall intensity and its correlation with landslide occurrence at highlands. As an area for further work, it may be useful to retrieve supplementary historical rainfall data from Hong Kong Observatory's records to refine the rainfall isohyets. The GEO is arranging the installation of additional automatic raingauges on natural terrain, and this would provide additional data in the long-term for the improvement of rainfall-natural terrain landslide assessments. When the additional data are available, further validation may be carried out on the rainfall-natural terrain

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landslide datasets to improve the data quality. For example, the 1985 rainfall-natural terrain landslide dataset has apparent anomalies, which deserve further validation.

(f) Other means of normalization of rainfall

The maximum rolling 24-hour rainfall was normalized by the location-specific mean annual rainfall in this study. This serves to give a better representation of the severity of the rainfall conditions at any specific location, since the overall rainfall intensity in Hong Kong is unevenly distributed. This normalization method was, however, not ‘prefect’, as illustrated in Figure 15 that the normalized maximum 24-hour rainfalls at different locations have different return period correlations. In theory, adopting rainfall return period (i.e. the rainfall is normalized in a manner that the normalized value of a given rainfall intensity is its corresponding return period) directly in the rainfall-natural terrain landslide correlation would give the best representation of the severity of rainfall. However, there is inadequate rainfall data readily available particularly on highlands and in other remote areas for establishing rainfall return period correlations.

(g) Consideration of rainfall intensities corresponding to different rainfall durations

The maximum rolling 24-hour rainfall has been found to be a useful rainfall criterion for correlation with landslide occurrence in Hong Kong. However, it is not the only criterion. A possible enhancement to the correlation models would be by associating natural terrain landslides also with rainfall of shorter duration (e.g. maximum rolling 3-hour) and with antecedent rainfall (e.g. 30-day rainfall). This can be performed efficiently in the GIS platform.

(h) Formulation of natural terrain landslide warning criteria

From the technical point of view, it is feasible to formulate a natural terrain landslide warning system based on the findings of the rainfall-natural terrain landslide correlation. The GEO has the capability to develop and implement the system on a GIS platform that incorporates consideration of terrain susceptibility classification, locations of vulnerable facilities, spatial and temporal distribution of rainfall and location-based rainfall near-casting. The additional technical development work described above on further improvement of the rainfall-natural terrain landslide correlation would also help to prepare for setting up the system when it is required.

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Table 1 - Comparison between Theoretical Annual Number and Actual Annual Number of Natural Terrain Landslides

Rainfall Scenario (Normalized Maximum Rolling 24-hour Rainfall)	Return Period, year	Actual Number of Natural Terrain Landslides	Storm-based Natural Terrain Landslide Density, (No./km^2)	Mean Annual Occurrence Rate	Theoretical Annual Number of Natural Terrain Landslides (see Note (1))
R1 (0.00 - 0.10)	1.23	428	0.0593	0.8130	31.7483
R2 (0.10 - 0.15)	3.55	1579	0.3241	0.2817	60.1255
R3 (0.15 - 0.20)	6.91	1450	0.9166	0.1447	87.3498
R4 (0.20 - 0.25)	21.87	828	1.7496	0.0457	52.6829
R5 (0.25 - 0.30)	69.62	497	4.9443	0.0144	46.7670
R6 (0.30 - 0.35)	281.84	478	9.9890	0.0035	23.3419
Total		5260			302.0154

Notes:
(1) Based on the Poisson statistical model, theoretical annual number of natural terrain landslides = storm-based natural terrain landslide density * mean annual occurrence rate. Alternatively, the theoretical annual number of natural terrain landslides can also be calculated by consideration of the storm-based hit area, which gives the same result.
(2) The actual number of natural terrain landslides from between 1985 and 2000 = 5260/16 = 329.
(3) Total area of natural terrain delineated by the 2000 development lines is 658.5228 km^2.
(4) The actual average annual natural terrain landslide density = 5260/658.5228/16 = 0.4992 no./km^2/yr.
The theoretical average annual natural terrain landslide density predicted by the storm-based correlation = 302.0154/658.5228 = 0.4586 no./km^2/yr.

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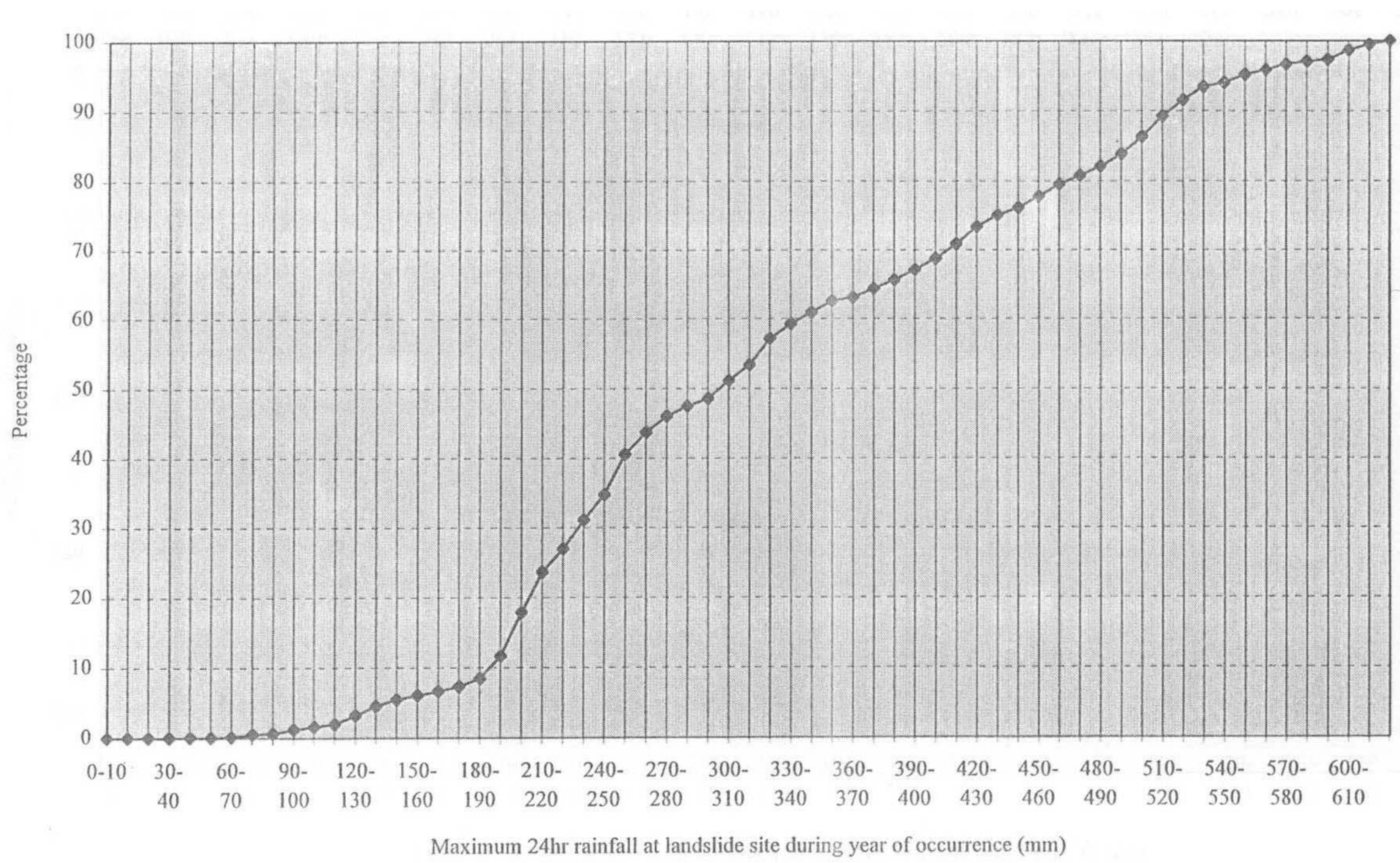
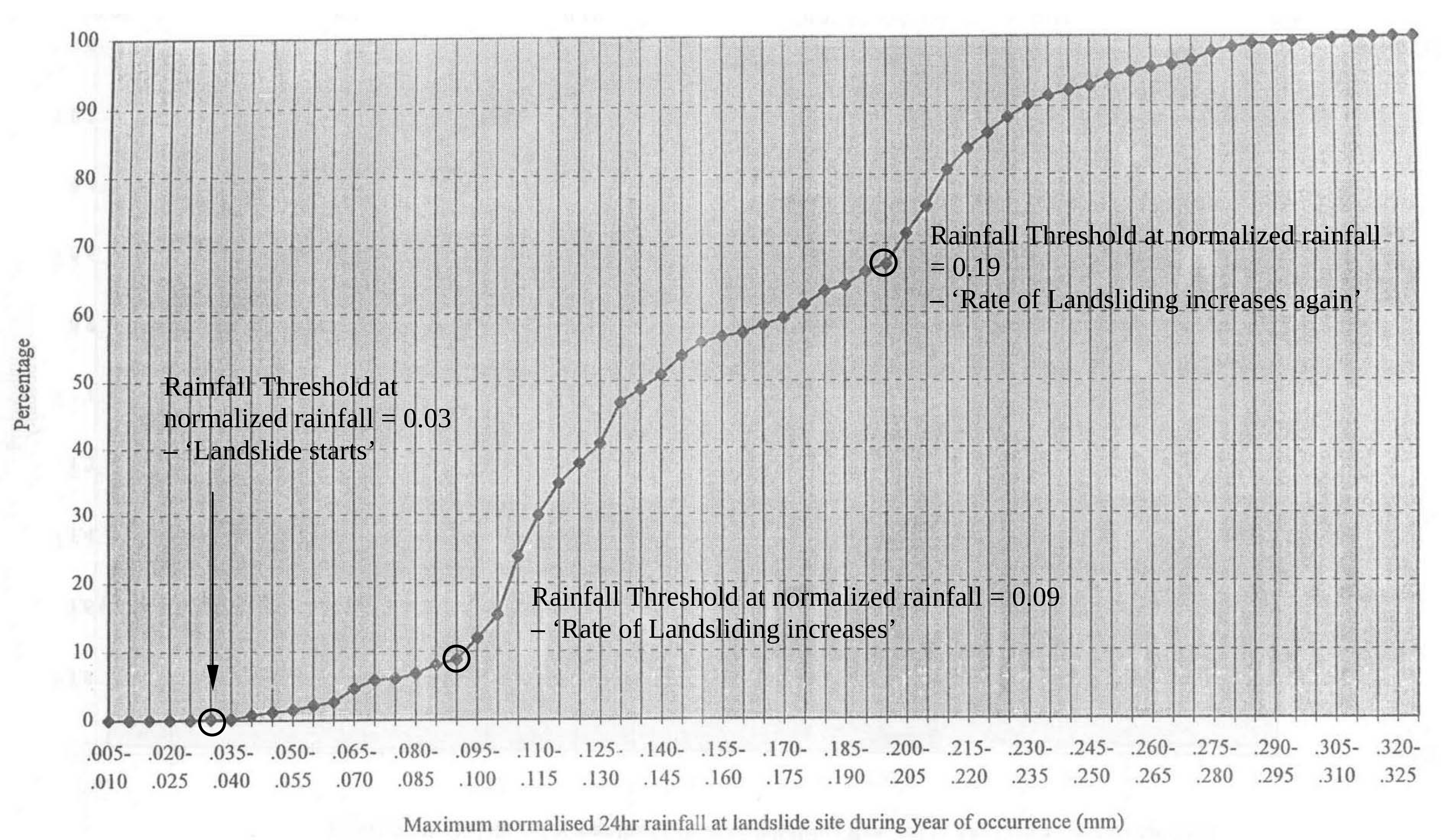


Note : Extracted from Evans (1997)

Figure 1 - Cumulative Percentage of Natural Terrain Landslides against Maximum Rolling 24-hour Rainfall (1985-1994)



Note : Extracted from Evans (1997)

Figure 2 - Cumulative Percentage of Natural Terrain Landslides against Normalized Maximum Rolling 24-hour Rainfall (1985-1994)

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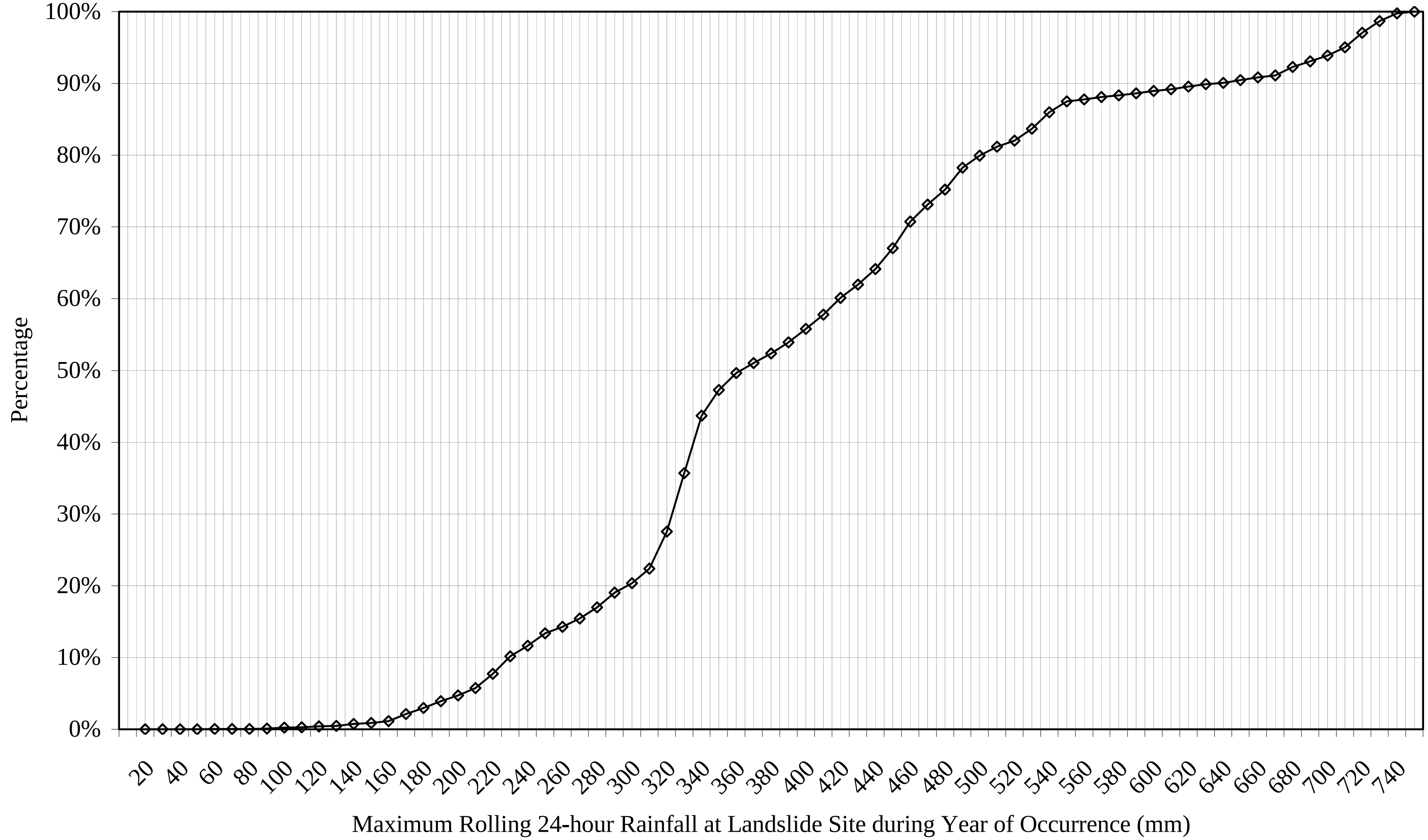

Figure 3 - Cumulative Percentage of Natural Terrain Landslides against Maximum Rolling 24-hour Rainfall (1985-2000)

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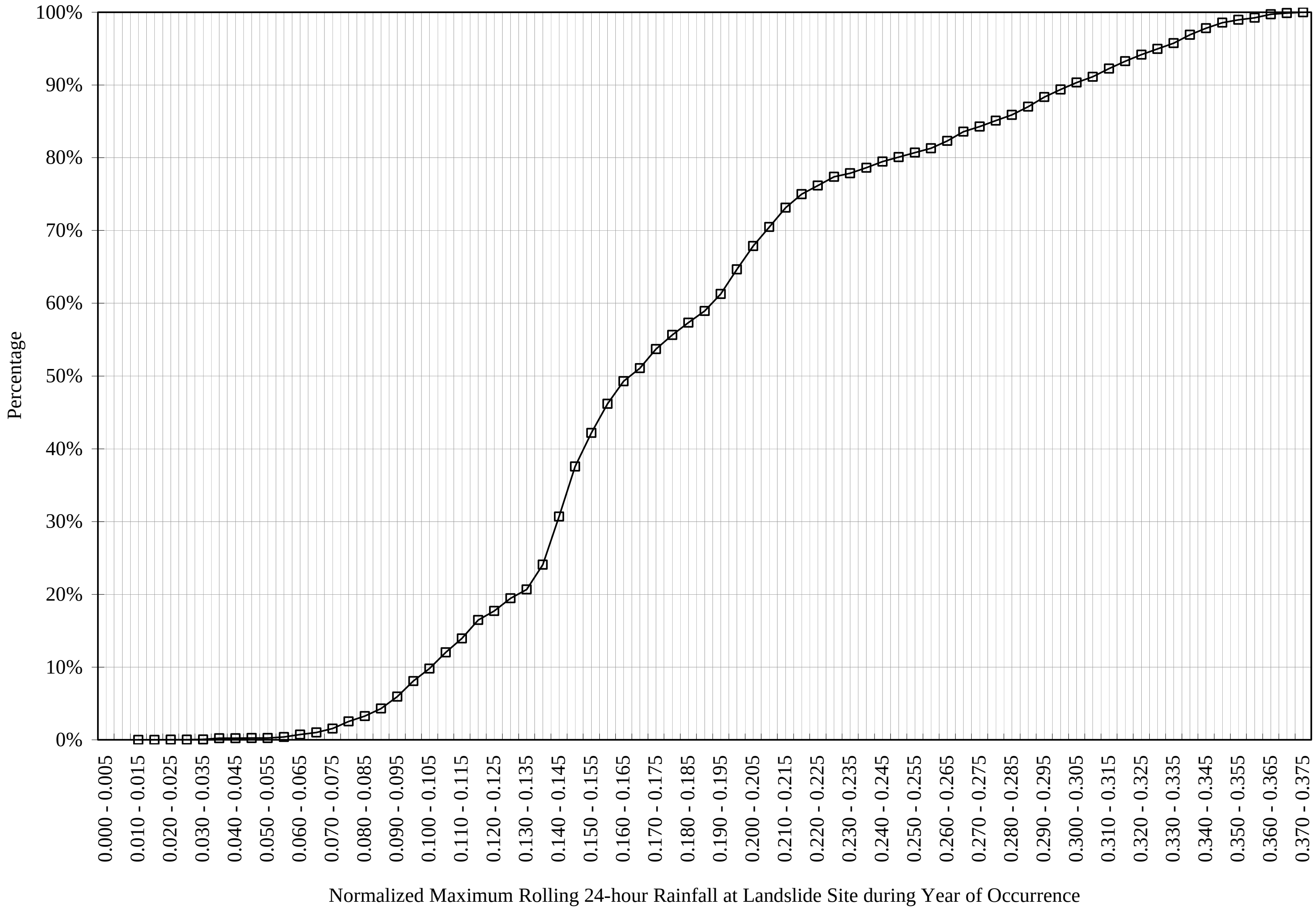

Figure 4 - Cumulative Percentage of Natural Terrain Landslides against Normalized Maximum Rolling 24-hour Rainfall (1985-2000)

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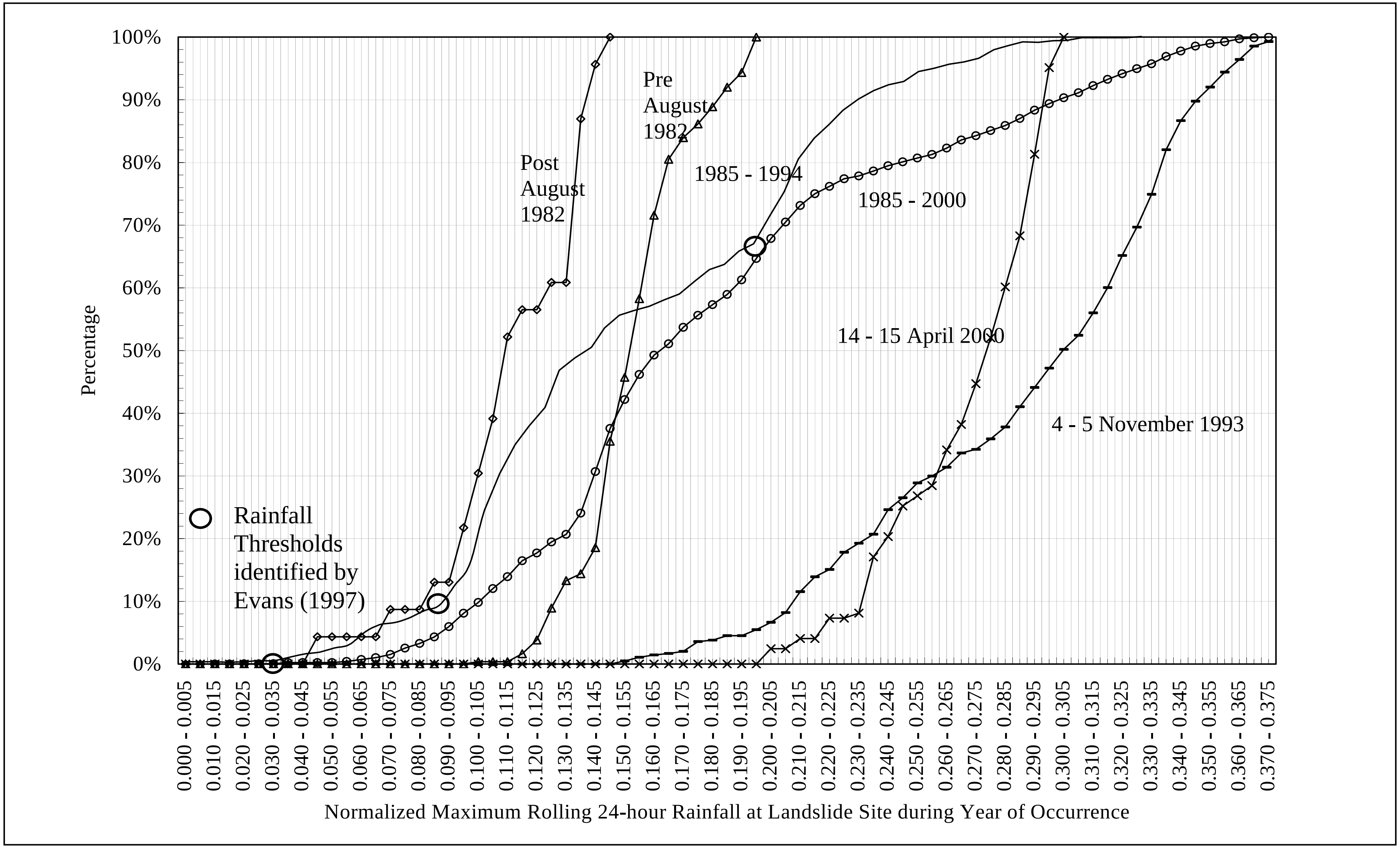

Figure 5 - Comparison of Different Plots of Cumulative Percentage of Natural Terrain Landslides against Normalized Maximum Rolling 24-hour Rainfall

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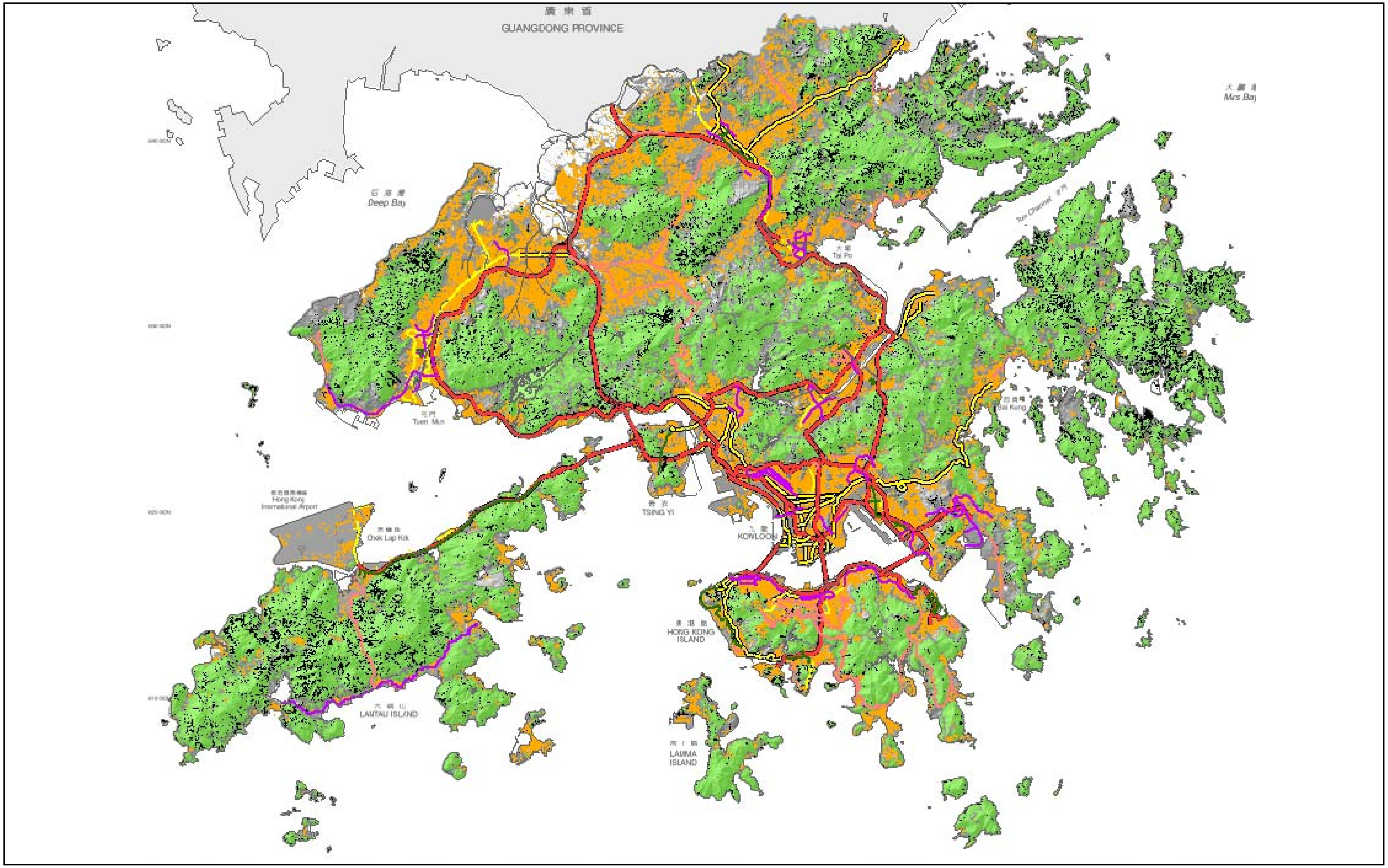

Figure 6 - Natural Terrain in Hong Kong Delineated by 2000 Development Lines

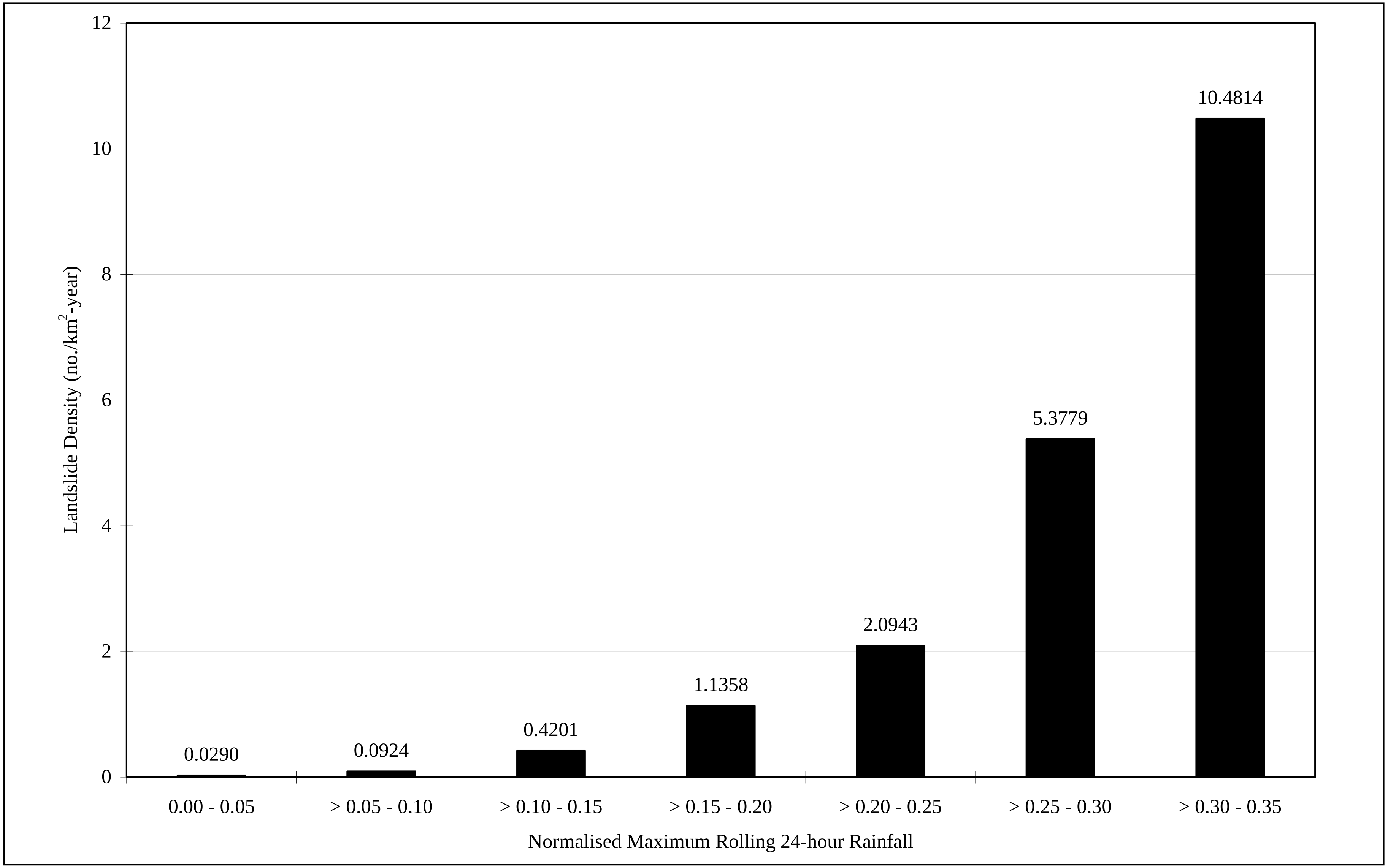

Figure 7 - Year-based Correlation between Normalized Maximum Rolling 24-hour Rainfall and Natural Terrain Landslide Density

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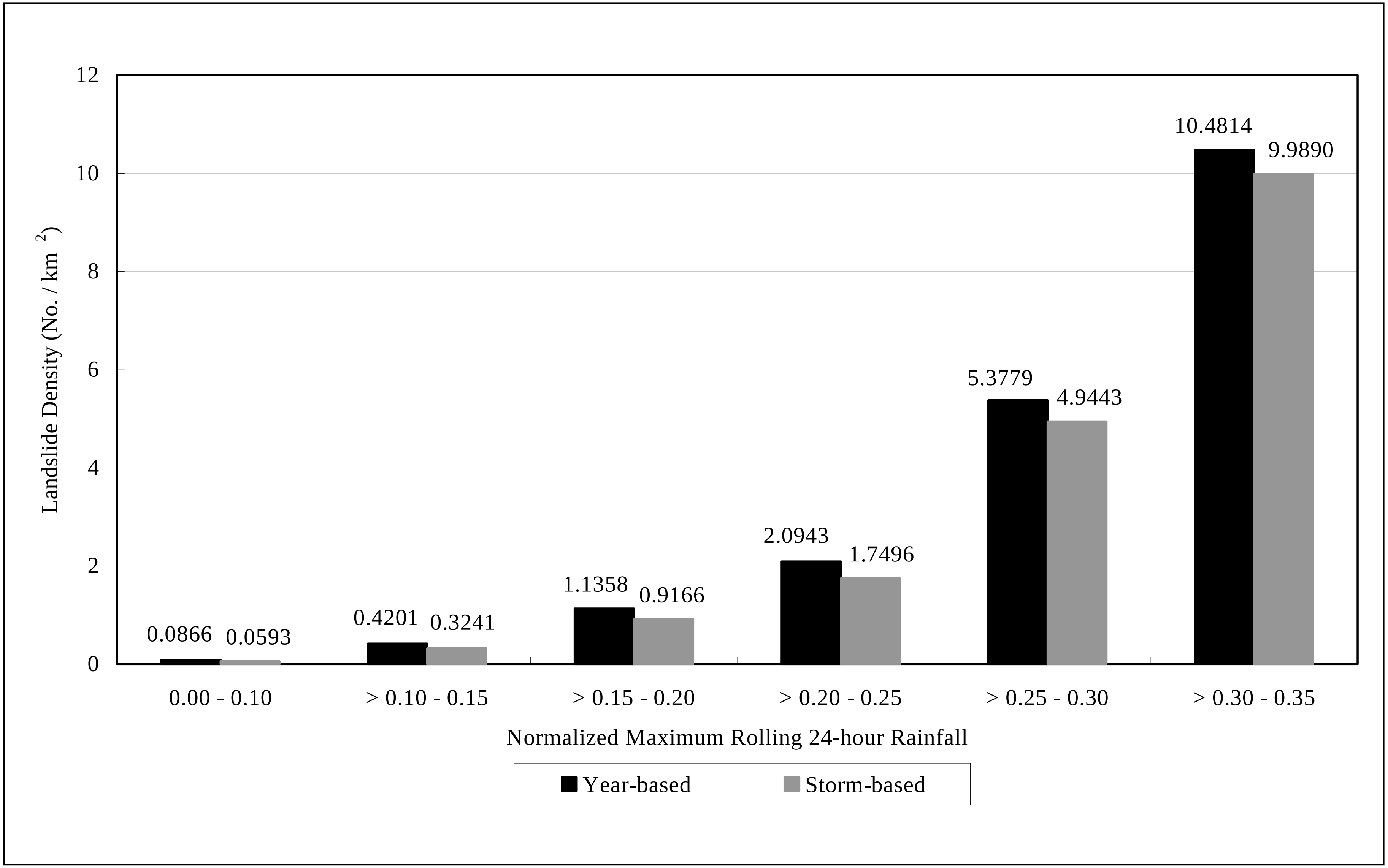

Figure 8 - Conversion of Year-based to Storm-based Rainfall-Natural Terrain Landslide Correlation

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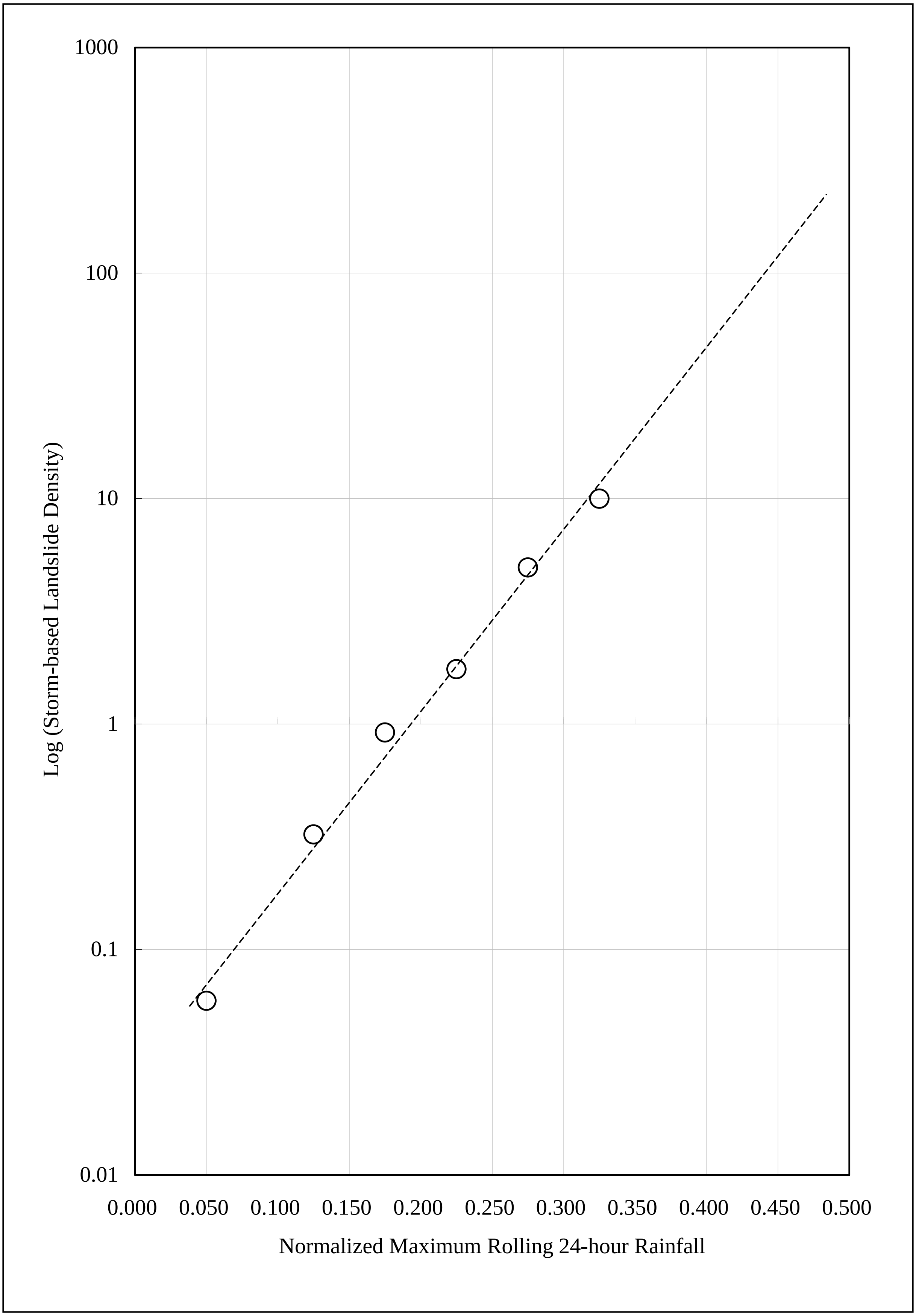

Figure 9 - Extrapolation of Natural Terrain Landslide Density

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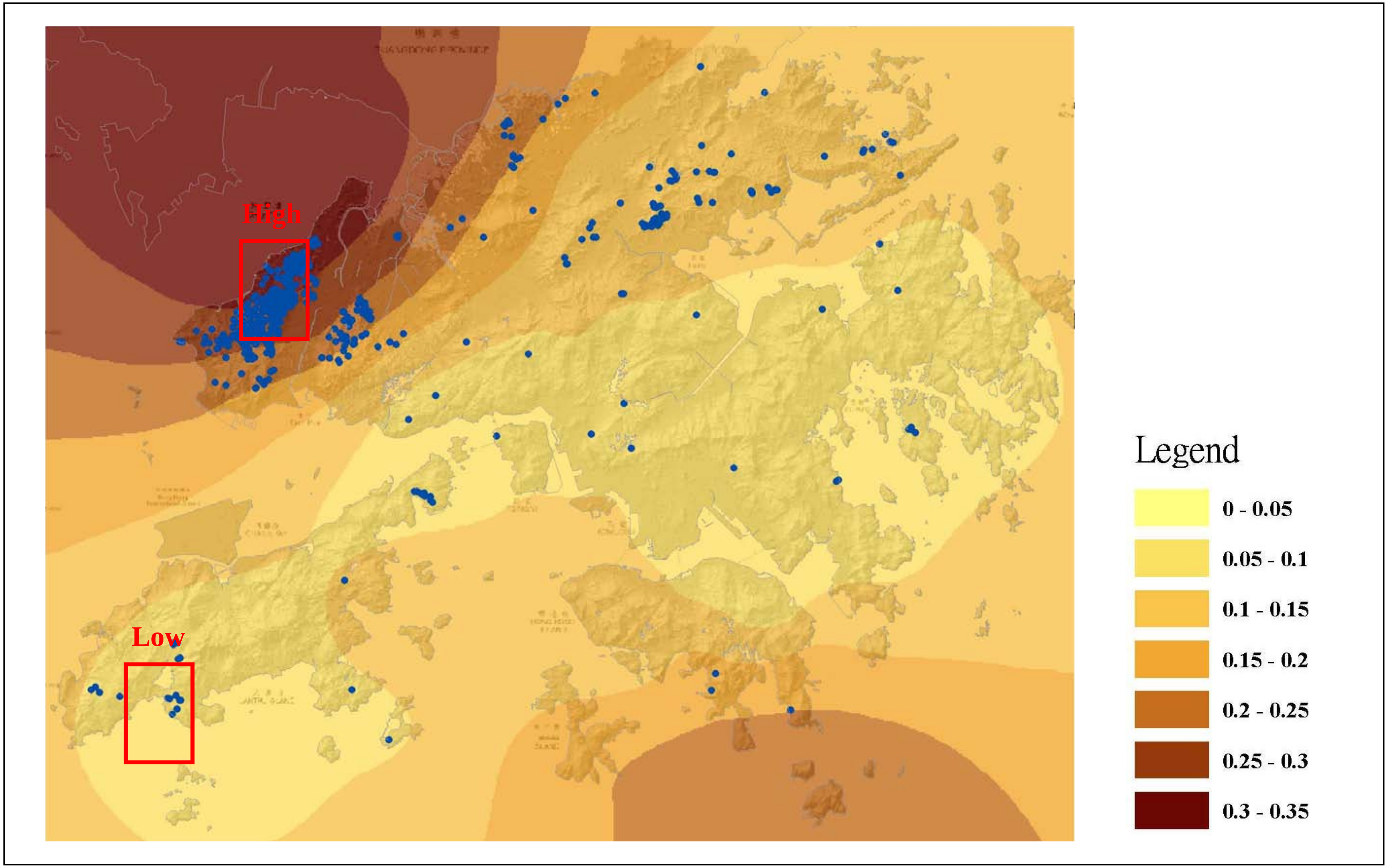

Figure 10 - Natural Terrain Landslides and Normalized Maximum Rolling 24-hour Rainfall in 2000

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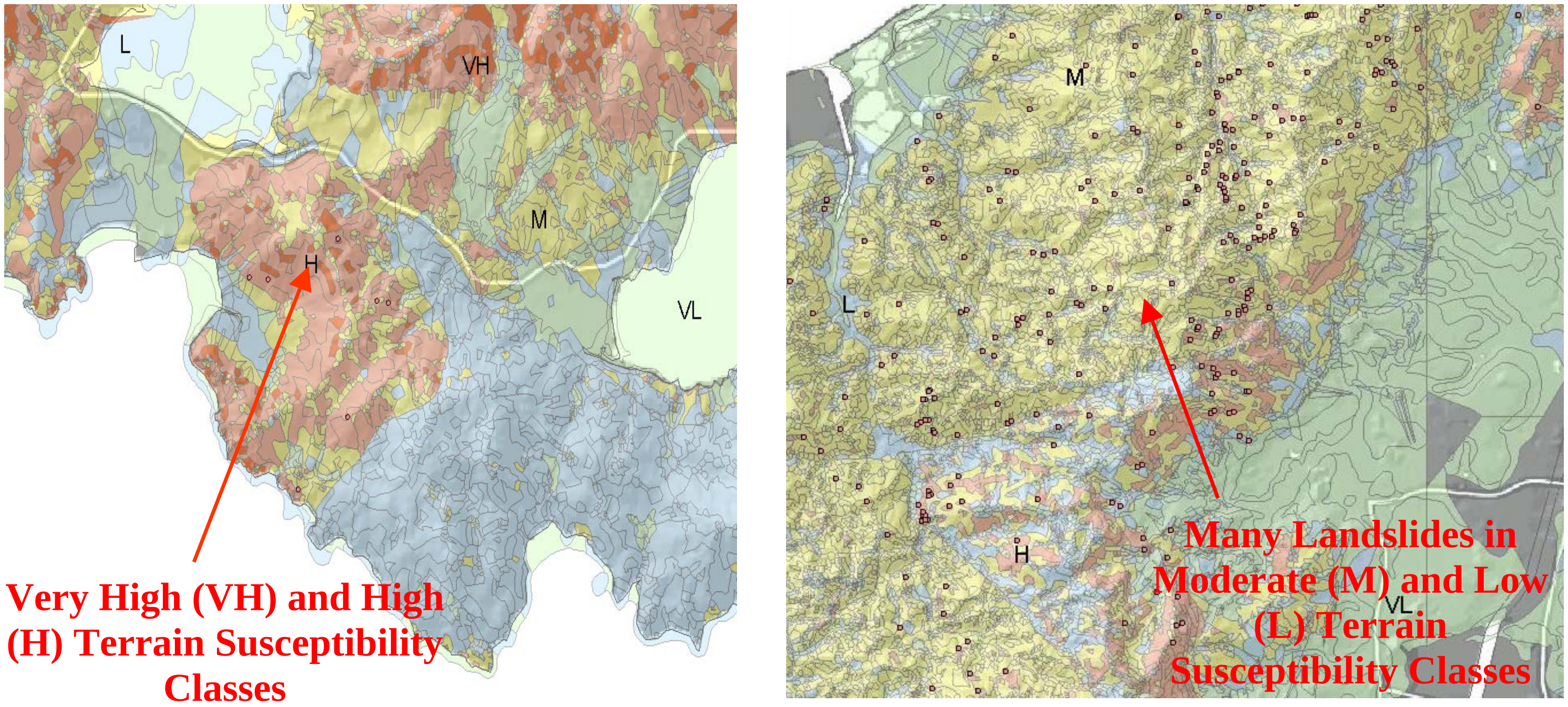
Location of Low Rainfall Intensity

Location of High Rainfall Intensity



Note : See Figure 10 for site location

Figure 11 - Terrain Susceptibility Classes at Location of High and Low Rainfall Intensity in 2000

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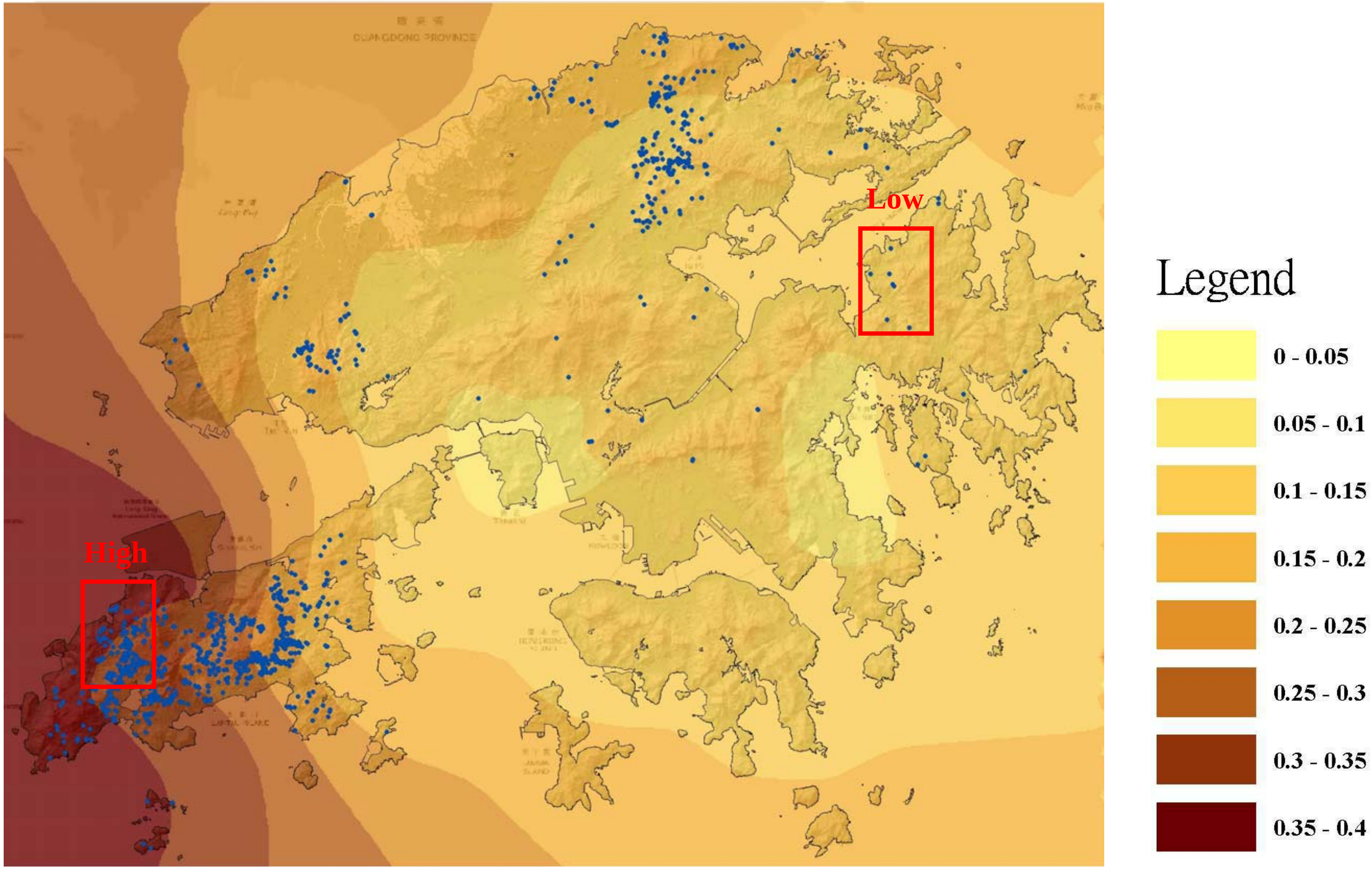

Figure 12 - Natural Terrain Landslides and Normalized Maximum Rolling 24-hour Rainfall in 1993

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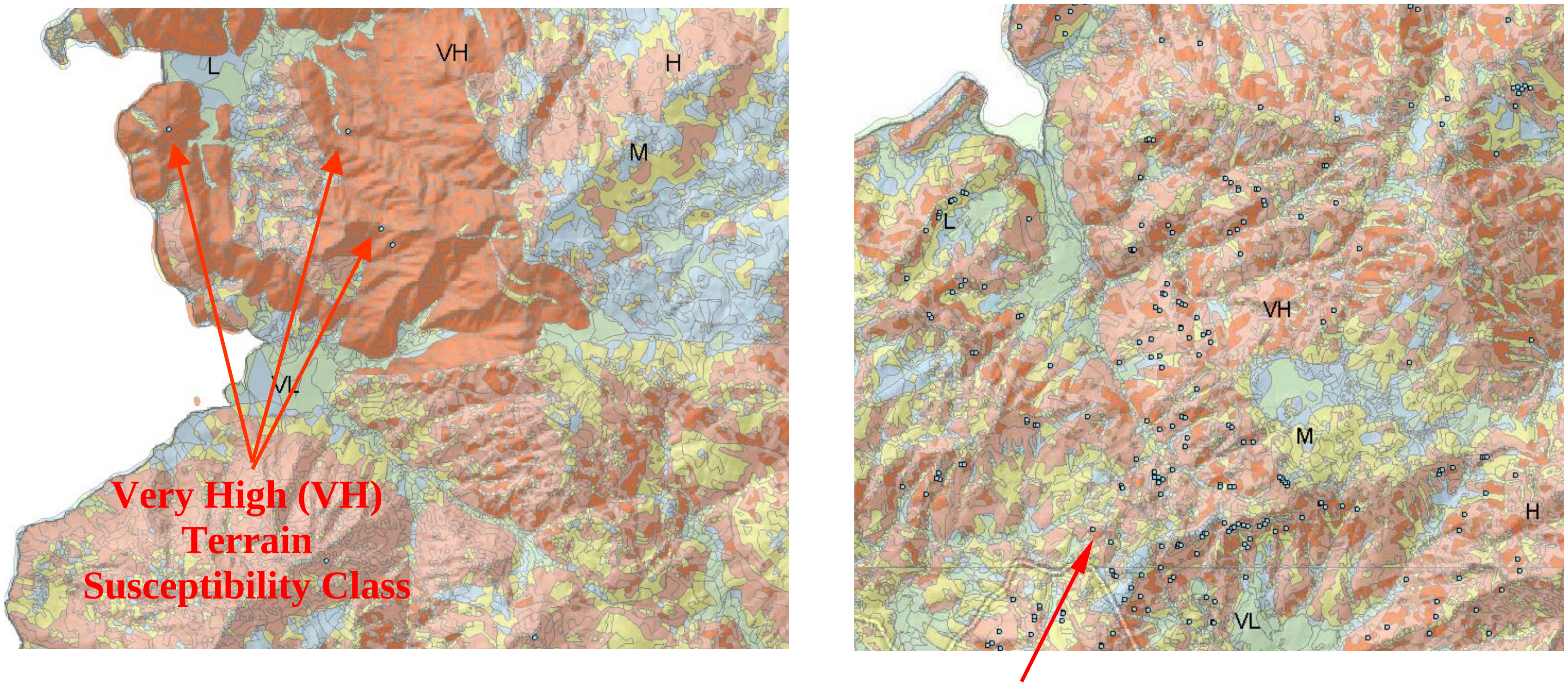
Location of Low Rainfall Intensity

Location of High Rainfall Intensity



Landslides in All Terrain Susceptibility Classes

Note : See Figure 12 for site location

Figure 13 - Terrain Susceptibility Classes at Location of High and Low Rainfall Intensity in 1993

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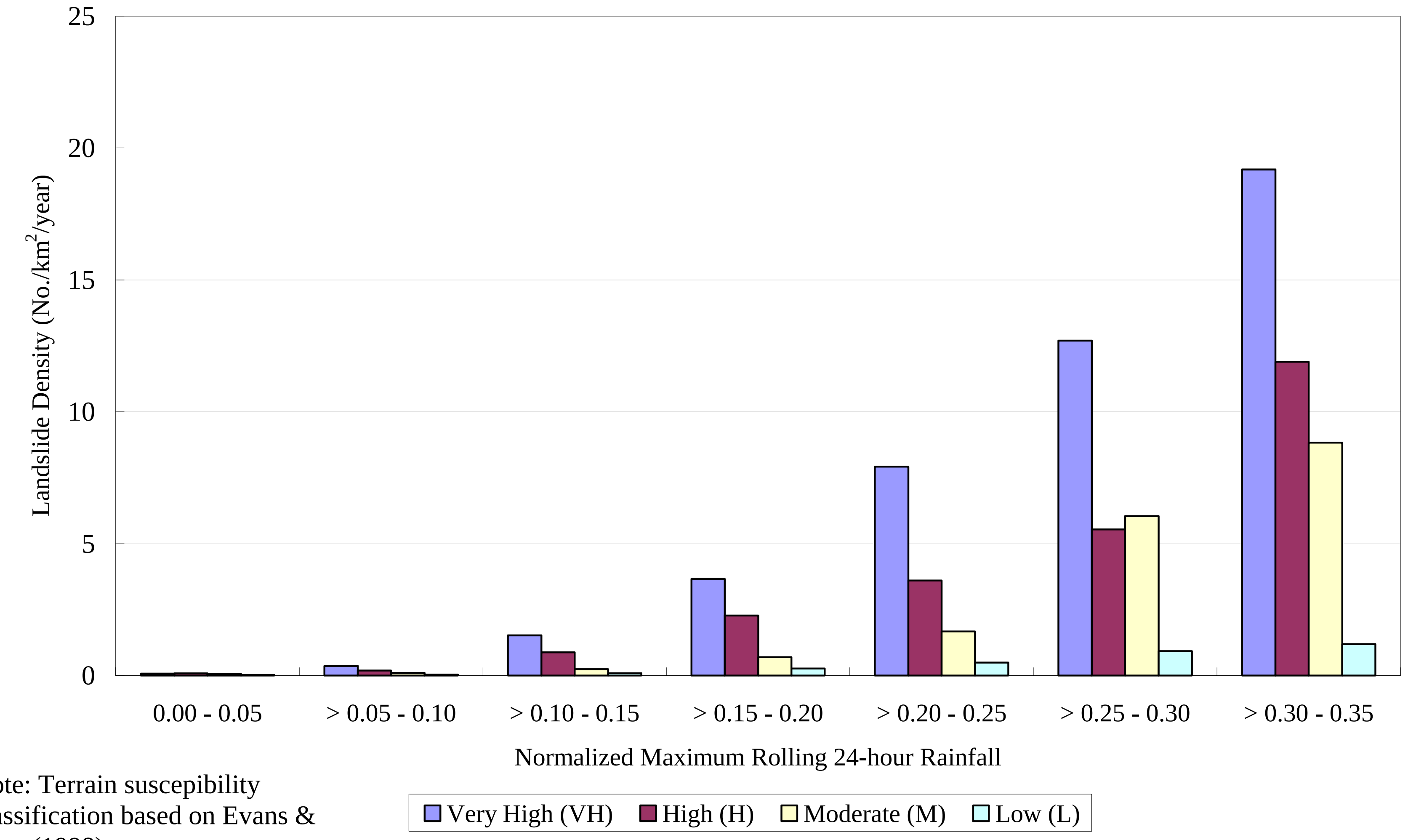

Note: Terrain suscepibility classification based on Evans & King (1998)

Figure 14 - Rainfall-Natural Terrain Landslide Correlations for Different Terrain Susceptibility Classes

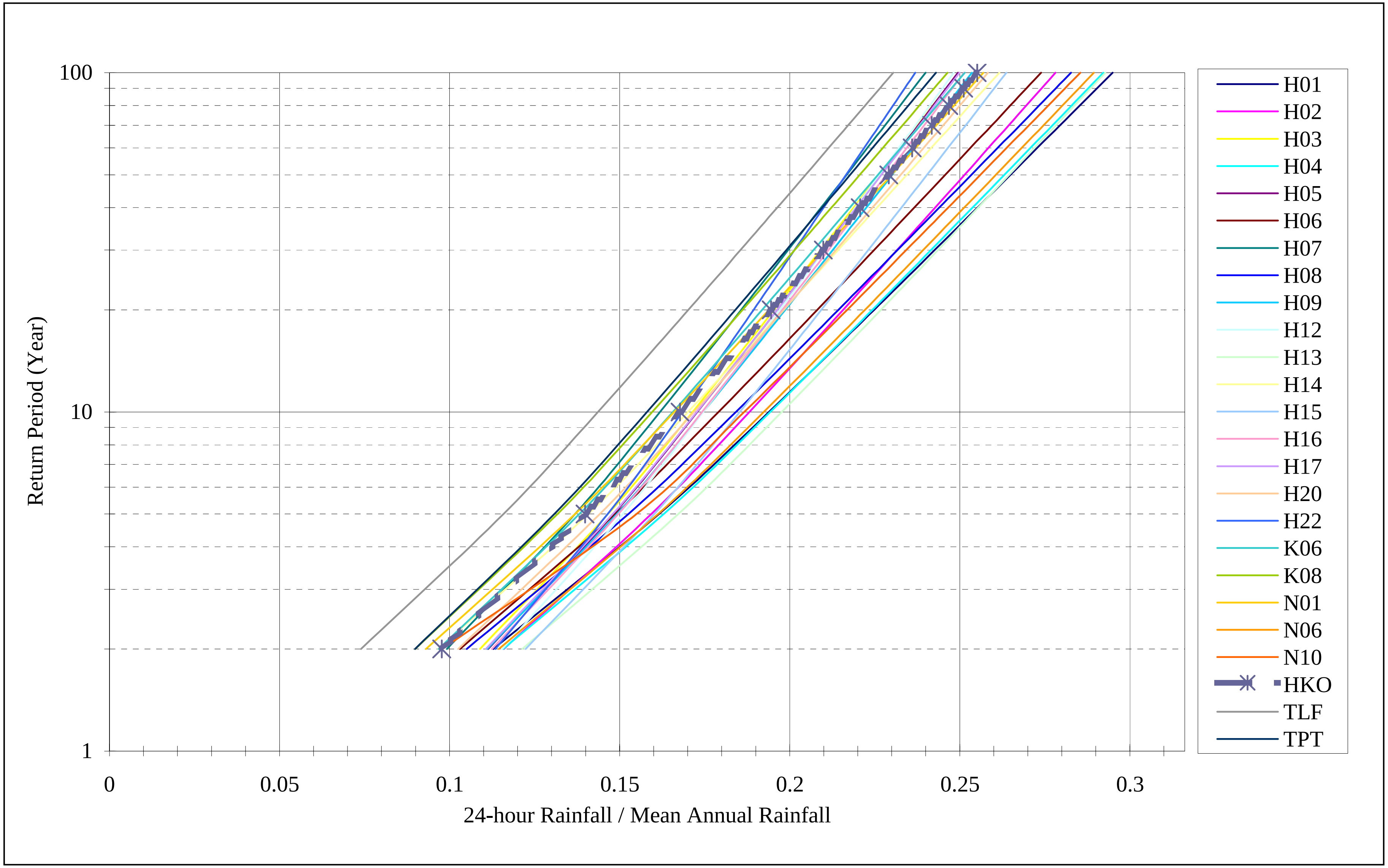

Figure 15 - Return Period Correlations for Different Normalized Rolling 24-hour Rainfall Intensities at Different Locations

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APPENDIX A

METHOD ADOPTED IN PRELIMINARY ASSESSMENY BY EVANS (1997)

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CONTENTS

A.1 INTRODUCTION

This Appendix summarizes the preliminary assessment by Evans (1997) on the relationship between rainfall and natural terrain landslide initiation.

A.2 ASSUMPTIONS

Rainfall and natural terrain landslide data between 1985 and 1994 were considered. It was assumed that a natural terrain landslide known to have taken place in a year occurred during the most severe rainstorm that resulted in the maximum rolling 24-hour rainfall at the landslide location in the year. Also, it was assumed that the natural terrain landslide was triggered by the maximum rolling 24-hour rainfall at the landslide location, i.e. it was initiated at the time when the rolling 24-hour rainfall reached the maximum value.

Due to the insufficient GIS capability at the time of the assessment, rainfall data that were readily available at the time were adopted and the rainfall-natural terrain landslide data were extracted manually, with approximation made in a subjective manner by visual inspection.

A.3 DATA

A.3.1 Rainfall

The assessment used the sets of isohyets of the maximum rolling 24-hour rainfall given in GEO's annual Rainfall and Landslide Reports for selected major rainstorms. Table A.1 lists the major rainstorm events considered in the assessment. Isohyets of mean annual rainfall were obtained from Lam and Leung (1995). The isohyets of maximum rolling 24-hour rainfall of the major rainstorm events in each year were transposed manually onto a 1:100,000 scale topographical plan of Hong Kong (Figure A.1).

It should be noted that these rainfall isohyets are strictly speaking not isohyets of the location-specific maximum rolling 24-hour rainfall that occurred in the year. They are isohyets of location-specific total rainfall in a 24-hour period. In this 24-hour period, the maximum rolling 24-hour rainfall was recorded at the location where the rolling 24-hour rainfall was the heaviest in the rainstorm.

A.3.2 Natural Terrain Landslides

The natural terrain landslides in each year were extracted from the Natural Terrain Landslide Inventory and were transferred manually to the 1:100,000 scale topographical plan containing the rainfall isohyets of the selected major rainstorms in the year.

A.4 ASSESSMENT OF RAINFALL-NATURAL TERRAIN LANDSLIDE RELATIONSHIP

For each natural terrain landslide, the corresponding rainfall data were extracted manually from the 1:100,000 plan showing the isohyets of maximum rolling 24-hour rainfall

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and the mean annual rainfall. The greatest value of the isohyets that bound each natural terrain landslide was taken as the maximum rolling 24-hour rainfall that triggered the natural terrain landslide. Mean annual rainfall at each natural terrain landslide location was read off from the nearest isohyet of mean annual rainfall. The normalized value was the maximum rolling 24-hour rainfall divided by the mean annual rainfall at the natural terrain landslide location.

Based on this method, a rainfall-natural terrain landslide database was compiled for all the natural terrain landslides from 1985 to 1994.

A.5 FINDINGS

Using the database, plots of cumulative distribution of natural terrain landslides against maximum rolling 24-hour rainfall and against normalized maximum rolling 24-hour rainfall were produced (Figure 1 and 2). Points of abrupt changes in the gradient was noted from the cumulative plot against normalized maximum rolling 24-hour rainfall. These points were taken as rainfall thresholds where significant increase in the number of natural terrain landslides would occur. The identified rainfall thresholds were:

	Threshold I Start of Landsliding	Threshold II Start of Landsliding at Medium Densities	Threshold III Start of Landsliding at High Densities
Mean Annual Rainfall <2000 mm (Deep Bay, North NT, outlying islands, coasts of Mirs Bay & Sai Kung)	40 - 60 mm (0.03)	130 -180 mm (0.09)	270 - 380 mm (0.19)
Mean Annual Rainfall 2000-2400 mm (most of the developed areas of Hong Kong, Kowloon & the NT, plus Lantau)	60 - 70 mm (0.03)	180 - 220 mm (0.09)	380 - 450 mm (0.19)
Mean Annual Rainfall >2400 mm (The Tai Mo Shan-Tate's Cairn-Ma On Shan central uplands, with Sha Tin)	70 - 110 mm (0.03)	220 - 340 mm (0.09)	450 - 720 mm (0.19)

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Evans (1997) has suggested some qualitative densities of natural terrain landslides while the limitations of the preliminary assessment were also noted as follows:

> *"The data manipulations carried out above are interesting, and show some possible rainfall thresholds, but it must be emphasized that the procedures used are not statistically rigorous. To take this analysis further, it is necessary to consider the reality of landslide distribution patterns. Without quantifying landslide densities - a complex task which will require use of the full NTLS GIS capability - it is possible to define some qualitative densities, as follows:*
>
> *Low density: less than 1 landslide per sq km*
> *Medium density: 1 to 10 landslides per sq km*
> *High density: over 10 landslides per sq km"*

A.6 <u>COMMENTS</u>

Based on the rigorous analysis carried out in this study with the use of GIS and statistical techniques, it is known that the rainfall thresholds identified by Evans (1997) are unreliable. Also, in respect of the qualitative densities, Evans (1997) has significantly underestimated the normalized rolling 24-hour rainfall intensities that correlate with the 'Moderate' and 'High' density zones.

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Table A.1 - Major Rainstorm Events from 1985 to 1994 Considered by Evans (1997)

Year	Day/Month	Maxima (24-hour) (mm)
1985	10 April	100
	25 June	150
	9 July	200
	26 August	140
	6 September	100
1986	12 May	150
	6 June	200
	4 July	200
	12 July	250
	11 August	250
1987	17 March	150
	7 April	200
	17 May	150
	22 May	100
	30 July	300
1988	20 July	240
1989	2 May	300
	21 May	500
1990	1 July	150
	11 September	240
1991	9 June	130
	15 October	150
1992	11 April	150
	8 May	300
	14 June	250
	19 June	100
	18 July	300
1993	11 June	200
	16 June	280
	25 September	200
	26 September	350
	5 November	700
1994	19 June	240
	22 July	800
	24 July	200
	25 July	250
	6 August	450
	10 August	200
	17 August	200

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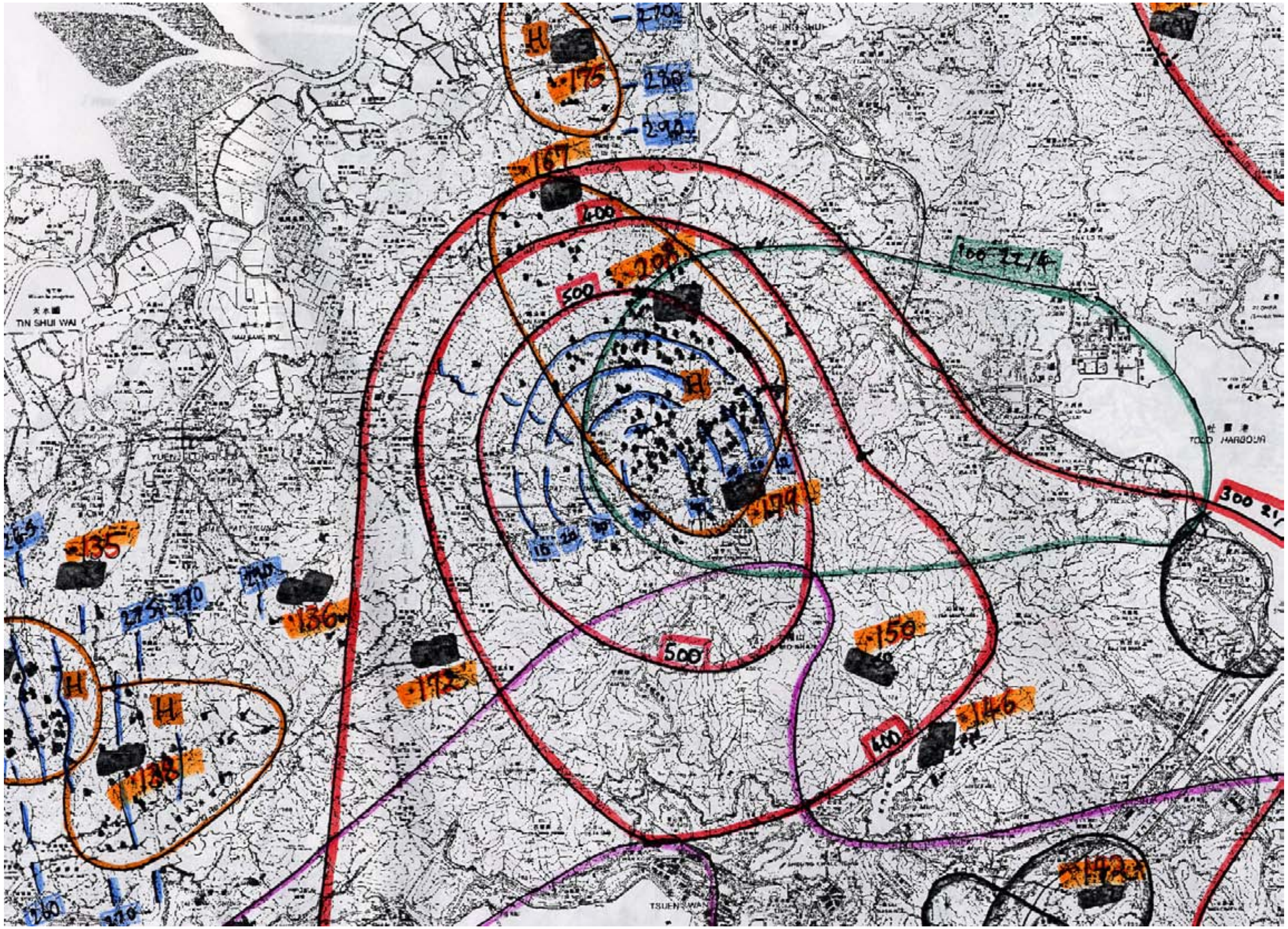

Figure A.1 - Part Print of 1:100,000 Topographical Plan with Isohyets of Major Rainstorm Events and Natural Terrain Landslides in 1989

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APPENDIX B

UPDATE OF CUMULATIVE PLOTS

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B.1 INTRODUCTION

This Appendix summarizes the update carried out in this study on the cumulative plots of rainfall-natural terrain landslide relationship.

B.2 ASSUMPTIONS

Rainfall and natural terrain landslide data between 1985 and 2000 were adopted in the update. The assumptions made in Evans (1997) regarding the maximum rolling 24-hour rainfall in triggering natural terrain landslides were adopted.

With the availability of GIS capability, geostatistical analysis was carried out to generate more comprehensive and reliable rainfall isohyets. Spatial analysis was performed to extract and correlate rainfall-landslide data. The analyses were undertaken on GEO's GIS platform.

B.3 DATA

B.3.1 Rainfall

Rainfall data from GEO's automatic raingauges were adopted to calculate the maximum rolling 24-hour rainfall that occurred in each year at each raingauge. Based on the calculated values of the location-specific maximum rolling 24-hour rainfall in each year, isohyets of the maximum rolling 24-hour rainfall were constructed by GIS geostatistical analysis, together with the application of the interpolation function of the computer software "SURFER". Unlike the isohyets adopted in Evans (1997), the isohyets constructed in this study are location-specific isohyets of genuine maximum rolling 24-hour rainfall. It should be noted that the maximum rolling 24-hour rainfalls at different locations may be recorded during different 24-hour periods.

The isohyets of mean annual rainfall were constructed with the use of GIS geostatistical techniques based on the available annual rainfall data between 1952 and 2000.

Isohyets of storm-based maximum rolling 24-hour rainfall were also constructed for selected major historical rainstorm events, during which many natural terrain landslides were known to have occurred. These include the rainstorms of May 1982, August 1982, 4-5 November 1993 and 14-15 April 2000.

B.3.2 Natural Terrain Landslides

The 1985 to 2000 natural terrain landslides that occurred on the natural hillsides delineated by the 2000 development lines were extracted from the Natural Terrain Landslide Inventory by GIS techniques. Table B.1 shows the number of natural terrain landslides that occurred in different years.

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B.4 ASSESSMENT OF RAINFALL-NATURAL TERRAIN LANDSLIDE RELATIONSHIP

For each natural terrain landslide, the corresponding maximum rolling 24-hour rainfall and the mean annual rainfall data were extracted and correlated by GIS spatial analysis. A spatial rainfall-landslide database was compiled for all the landslides from 1985 to 2000 on GEO's GIS platform.

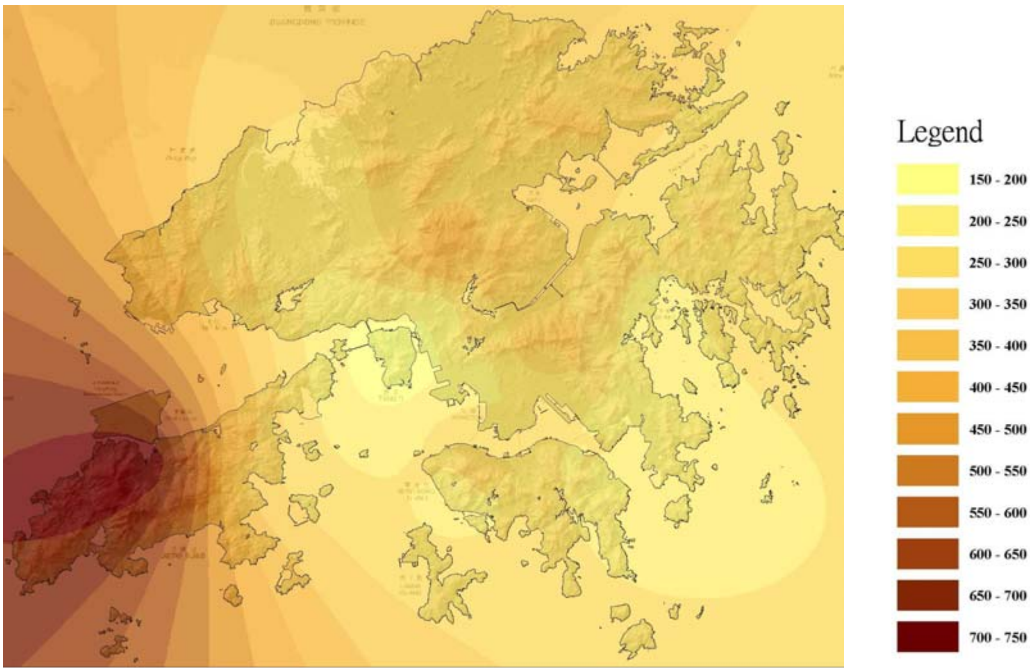
B.5 FINDINGS

The plots of cumulative distribution of natural terrain landslides against maximum 24-hour rainfall and normalized maximum 24-hour rainfall were produced using the database compiled in Section B.4 above. Similarly, cumulative plots were prepared for the selected major historical rainstorms.

B.6 EXAMPLE

An example is given below to illustrate the steps taken in the assessment. In this example, rainfall (in millimetres) and natural terrain landslide data of 1993 are shown.

Step 1: Construct the isohyets of maximum rolling 24-hour rainfall by geostatiscal analysis



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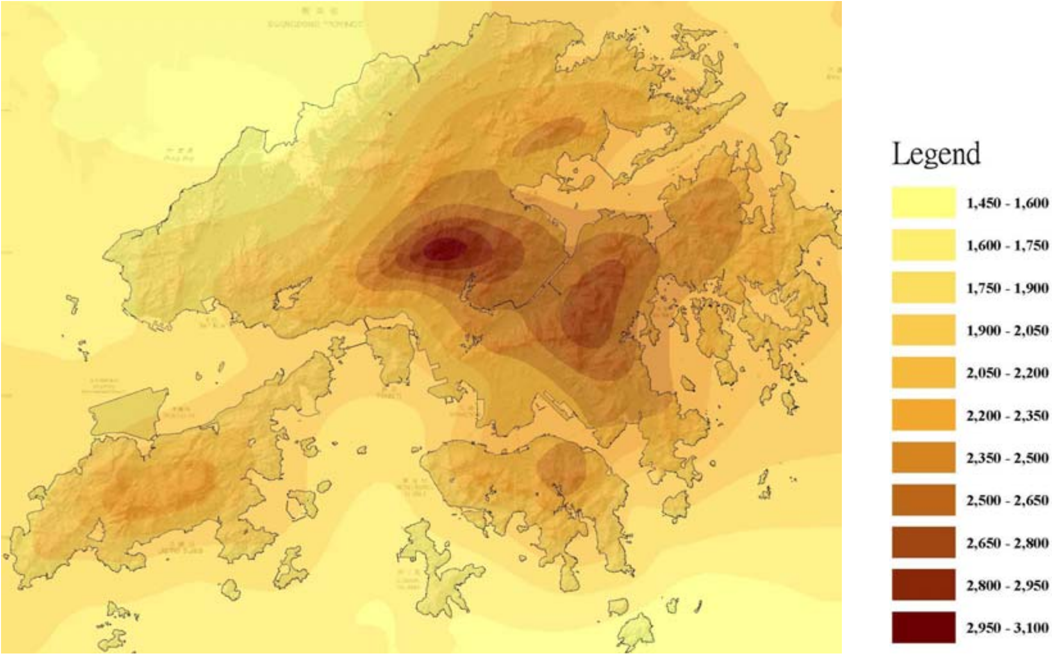
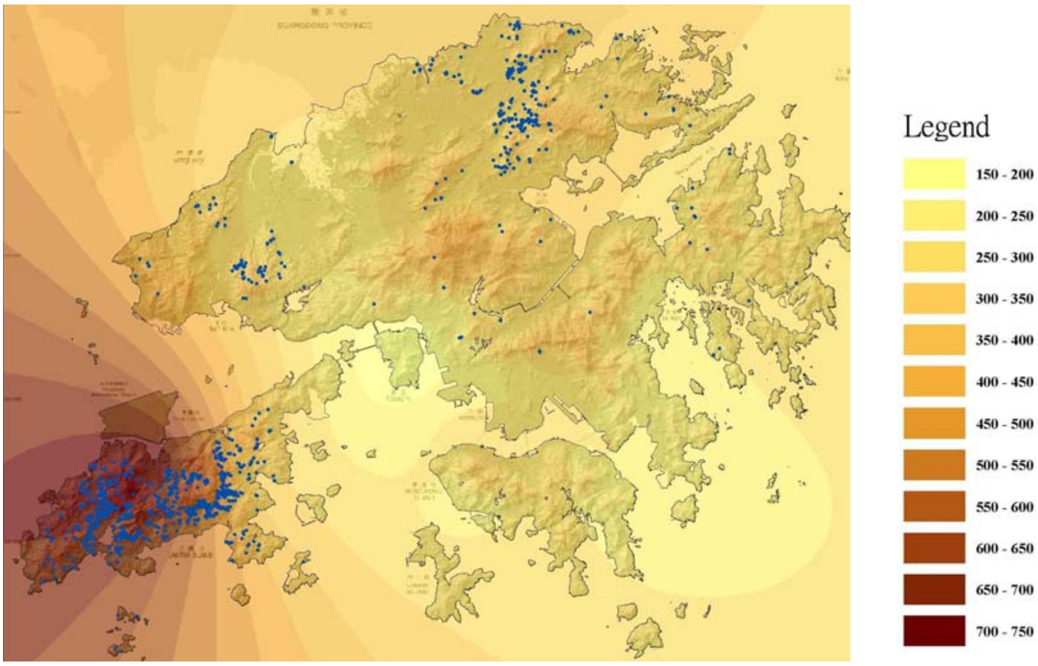
Step 2: Construct the isohyets of mean annual rainfall by geostatistical analysis



Step 3: Superimpose the natural terrain landslides onto the maximum rolling 24-hour rainfall GIS layer



Step 4: Extract the maximum rolling 24-hour rainfall at the natural terrain landslide locations by spatial analysis

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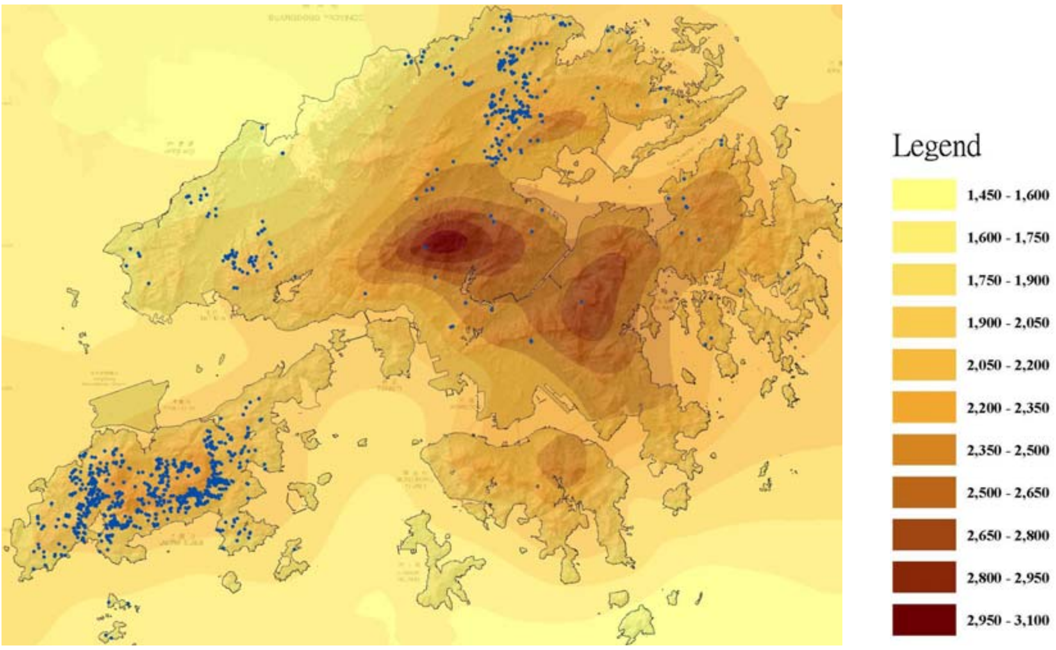
Step 5: Superimpose the natural terrain landslides onto the mean annual rainfall GIS layer



Step 6: Extract the mean annual rainfall at the natural terrain landslide locations by spatial analysis

Step 7: Calculate the normalized maximum rolling 24-hour rainfall at the natural terrain landslide locations

Step 8: Repeat the above steps for other years to establish a database of 16 years of data on natural terrain landslides and their corresponding absolute and normalized maximum rolling 24-hour rainfall

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Table B.1 - Number of Natural Terrain Landslides from 1985 to 2000

Year	Number of Natural Terrain Landslides
1985	86
1986	46
1987	10
1988	38
1989	442
1990	14
1991	7
1992	392
1993	1269
1994	762
1995	189
1996	67
1997	251
1998	374
1999	763
2000	630
Total	5340

APPENDIX C

CORRELATION BETWEEN RAINFALL AND NATURAL TERRAIN LANDSLIDE OCCURRENCE

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CONTENTS

C.1 INTRODUCTION

This Appendix summarizes the method adopted in establishing the year-based correlation between rainfall and natural terrain landslides using a rigorous spatial analysis. Unlike the method adopted in deriving the cumulative plots, natural terrain without landslide occurrence in a given year were considered in the rigorous spatial analysis.

C.2 DATA AND ASSUMPTIONS

Rainfall and natural terrain landslide data between 1985 and 2000 were considered. Isohyets of maximum rolling 24-hour rainfall in each year, as well as isohyets of mean annual rainfall from 1952 to 2000, were constructed as described in Section B.3 of Section B.

Natural terrain landslides that occurred from 1985 to 2000 on the natural hillsides delineated by the 2000 development lines were adopted.

C.3 ASSESSMENT OF RAINFALL-NATURAL TERRAIN LANDSLIDE CORRELATION

The key steps are described in Section 4.1. In each year, spatial locations of the natural terrain subject to different ranges of normalized maximum rolling 24-hour rainfall, viz. 0.00-0.05, >0.05-0.10, >0.10-0.15, >0.15-0.20, >0.20-0.25, >0.25-0.30, >0.30-0.35, were identified on a GIS platform. The area of natural terrain subject to each range of rainfall intensity and the number of natural terrain landslides that occurred on the terrain were assessed by spatial analysis. This analysis was performed for each year from 1985 to 2000, to compile a spatial rainfall-landslide database.

From this database, the total year-based area of natural terrain subject to each range of rainfall intensity from 1985 to 2000 and the total number of natural terrain landslides occurred on the natural terrain were calculated (Table C.1). Based on the figures, a year-based correlation between rainfall and natural terrain landslide density was established.

C.4 EXAMPLE

An example is given below to illustrate the steps taken in the correlation. In this example, rainfall (in millimetres) and natural terrain landslide data of 1993 are shown.

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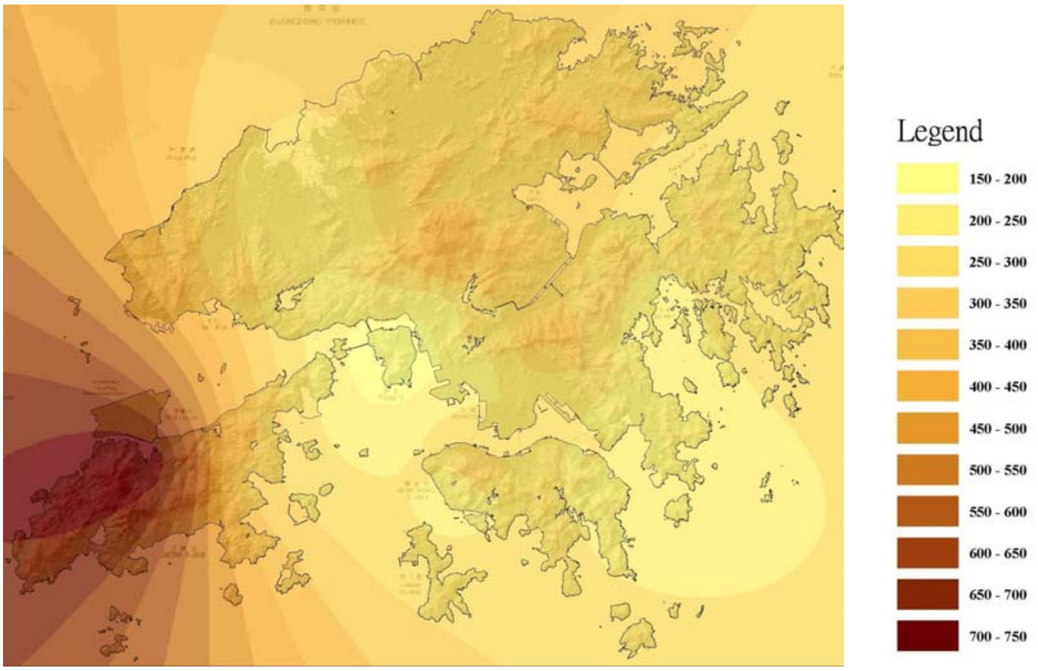
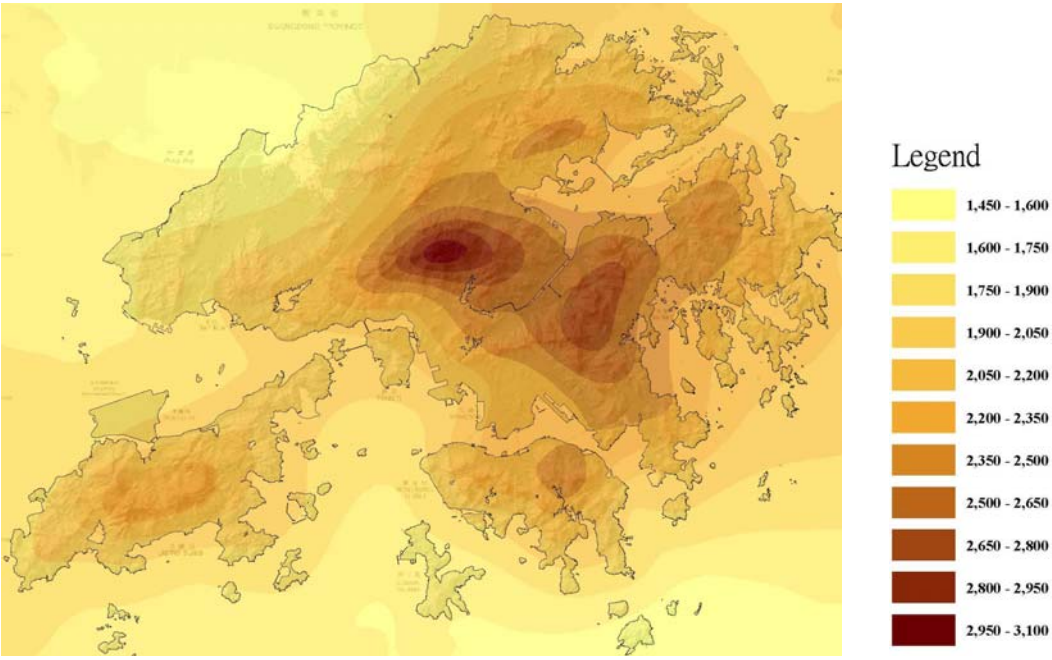
Step 1: Construct the isohyets of maximum rolling 24-hour rainfall by geostatistical analysis



Step 2: Construct the isohyets of mean annual rainfall by geostatistical analysis



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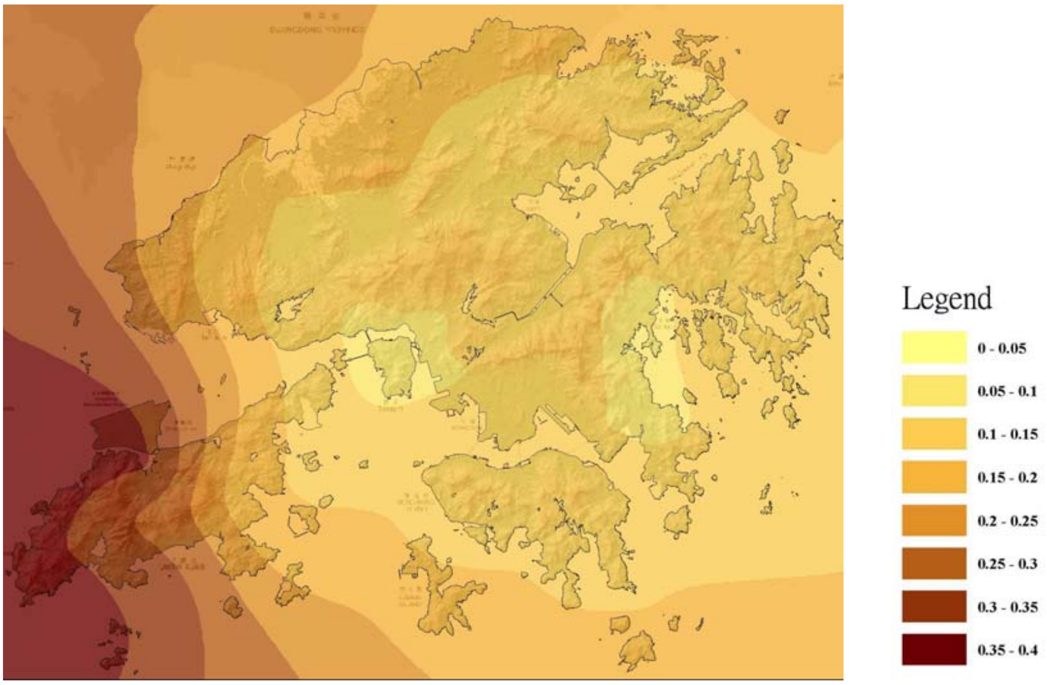
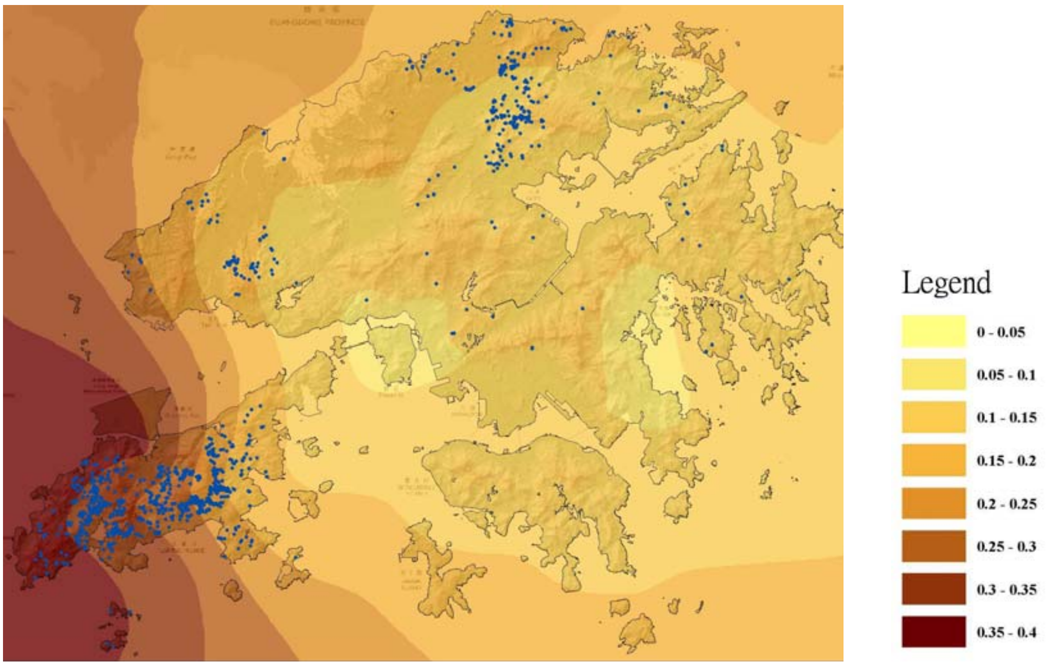
Step 3: Construct the isohyets of normalized maximum rolling 24-hour rainfall and reclassify the isohyets into seven rainfall ranges by GIS functionalities



Step 4: Count the number of natural terrain landslides in each rainfall range and calculate the natural terrain area in each rainfall range by spatial analysis



Step 5: Repeat the above steps for other years to establish a database of 16 years of data on the total number of natural terrain landslides and the total natural terrain area subject to each rainfall range

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Table C.1 - Number of Natural Terrain Landslides and Natural Terrain Area for Each Rainfall Range

Year	Normalized Maximum 24-hour Rainfall													
	0.00 - 0.05		> 0.05 - 0.10		> 0.10 - 0.15		> 0.15 - 0.20		> 0.20 - 0.25		> 0.25 - 0.30		> 0.30 - 0.35	
	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)	No. of NTLs (No.)	Natural Terrain Area (km^2)
1985	11	123.78	72	488.95	3	45.79	0	0.00	0	0.00	0	0.00	0	0.00
1986	1	118.67	16	290.46	29	249.39	0	0.00	0	0.00	0	0.00	0	0.00
1987	0	0.00	2	260.43	7	381.35	1	16.74	0	0.00	0	0.00	0	0.00
1988	0	2.81	32	536.30	6	119.41	0	0.00	0	0.00	0	0.00	0	0.00
1989	0	0.00	27	324.93	205	234.53	210	99.06	0	0.00	0	0.00	0	0.00
1990	0	0.00	10	647.01	4	11.52	0	0.00	0	0.00	0	0.00	0	0.00
1991	1	203.35	6	451.02	0	4.15	0	0.00	0	0.00	0	0.00	0	0.00
1992	0	0.00	41	207.78	53	304.47	116	76.01	182	68.62	0	1.64	0	0.00
1993	0	0.00	1	34.67	216	402.47	194	99.79	240	36.70	171	24.26	367	32.73
1994	0	0.00	3	14.81	395	315.09	234	188.18	94	90.91	33	44.26	3	5.28
1995	0	0.00	81	228.17	84	347.20	22	72.53	2	10.62	0	0.00	0	0.00
1996	0	0.00	30	374.29	20	258.20	17	26.03	0	0.00	0	0.00	0	0.00
1997	0	0.00	4	36.80	39	319.08	154	245.16	49	50.12	5	6.91	0	0.44
1998	0	0.00	0	30.10	222	382.91	132	202.96	20	42.55	0	0.00	0	0.00
1999	0	0.00	43	232.58	219	161.17	345	197.39	156	67.39	0	0.00	0	0.00
2000	0	0.00	47	333.27	77	221.59	25	52.73	85	28.45	288	15.34	108	7.15
Total	13	448.62	415	4491.56	1579	3758.35	1450	1276.58	828	395.35	497	92.42	478	45.60

Note: Data for normalized maximum rolling 24-hour rainfall exceeding 0.35 are scarce and not representative for the purpose of the establishment of rainfall-natural terrain landslide correlation.

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APPENDIX D

CONVERSION OF YEAR-BASED CORRELATION TO STORM-BASED CORRELATION

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CONTENTS

D.1 INTRODUCTION

This Appendix summarizes the statistical conversion of the year-based rainfall-natural terrain landslide correlation to a storm-based correlation.

D.2 STATISTICAL APPROACH ADOPTED

The year-based correlation is statistically related to the storm-based correlation. Hence, the year-based correlation can be converted to a storm-based correlation by the application of statistical techniques. In the conversion carried out in this study, the Poisson statistical model was adopted, i.e. under a Poisson distribution, the probability of the number of occurrence (X_t) in a given time interval (t) is:

$$P(X_t = x) = \frac{(\nu t)^x}{x!} e^{-\nu t} \quad , x = 0,1,2,.......$$

where ν is the mean occurrence rate.

Six rainfall scenarios R1 to R6 that correspond to the following ranges of normalized maximum rolling 24-hour rainfall were considered: 0.00 - 0.10; >0.10 - 0.15; >0.15 - 0.20; >0.20 - 0.25; >0.25 - 0.30 and >0.30 - 0.35.

D.3 METHOD OF CONVERSION

The conversion involves the following key steps:

(a) Reclassify the normalized maximum rolling 24-hour rainfall into the six rainfall scenarios: R1 = 0.00 - 0.10; R2 = >0.10 - 0.15; R3 = >0.15 - 0.20; and R4 = >0.20 - 0.25; R5 = >0.25 - 0.30; R6 = >0.30 - 0.35. The year-based rainfall-natural terrain landslide correlation, in terms of natural terrain landslide density for each of the rainfall scenarios, was established using the method described in Appendix C. The results are given in Table D.1.

(b) The sets of curve on return period against normalized maximum rolling 24-hour rainfall, calculated for different raingauge locations are shown in Figure D.1. A representative curve for natural terrain was chosen (see Figure D.1 and discussion given in Item (f) of Section 5). From this curve, the return periods of the normalized maximum rolling 24-hour rainfall at the boundaries of R1 to R6, i.e. 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35, were identified (Figure D.1). By the application of the Poisson statistical model, the annual probability of occurrence and the corresponding return period were calculated for each rainfall scenario (Figure D.2, and Tables D.2 and D.3);

(c) As shown in Table D.4, rainfall scenario R1 has a total year-based hit area of 4940.1804 km^2 from 1985 to 2000, based on findings from spatial analysis of the historical rainfall-natural terrain landslide data. However, there is the probability that part of the natural terrain might have been affected more than once in a year by

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rainfall scenario R1. This probability, and hence the corresponding percentage of the 4940.1804 km^2 that would in theory be hit more than once by rainfall scenario R1 could be calculated with the use of the Poisson statistical model. The results of the calculation are given in Table D.4. From the calculation, an adjustment factor of 1.4610 was determined for rainfall scenario R1. This adjustment factor means that, for rainfall scenario R1, the storm-based hit area was 1.4610 times of the year-based hit area, i.e. in theory the equivalent area of natural terrain hit by rainfall scenario R1 once was 1.4610 * 4940.1804 km^2 = 7217.5468 km^2 (Table D.4). Similarly, the adjustment factor and equivalent storm-based hit area were calculated for other rainfall scenarios as shown in Table D.4.

(d) For rainfall scenario R1, the storm-based natural terrain landslide density was calculated as the number of historical natural terrain landslides under this scenario divided by the theoretical storm-based hit area, i.e. 428/7217.5468 km^2 = 0.0593 No./km^2 (Table D.6).

(e) From spatial analysis, the number of historical natural terrain landslides that had occurred on natural terrain categorized under rainfall scenario R2, i.e. natural terrain with normalized maximum rolling 24-hour rainfall within the range of rainfall scenario R2, is 1579 (Table D.5). However, this is not the true number of natural terrain landslides that occurred in rainfall scenario R2, because there is a probability that part of the natural terrain concerned (year-based area = 3758.3471 km^2, Table D.4) was also hit once or more by rainfall scenario R1. By applying the Poisson statistical model, this probability (i.e. 1 - 0.4435 = 0.5565) and hence the theoretical year-based hit area within the 2091.5202 km^2 i.e. 0.5565 * 3758.3471 = 2091.5202 km^2) were found. Then, the theoretical number of natural terrain landslides that would have been due to rainfall scenario R1 hitting part of natural terrain categorized under rainfall scenario R2 was calculated in Table D.5 as 2091.5202 * 0.0866 = 181.1949, where as 0.0866 is the year-based natural terrain landslide density for rainfall scenario R1 (Table D.1). Hence, the number of natural terrain landslides that would have been solely due to rainfall scenario R2 and occurred on natural terrain hit by rainfall scenario R2 was found to be 1579 - 181.1949 = 1397.8051. This is denoted as the adjusted number of natural terrain landslides in Table D.5.

(f) Following the method described in Item (e) above, the adjusted number of natural terrain landslides for scenario R3 was calculated by deducting those that would theoretically have occurred due to rainfall scenarios R1 and R2 (Table D.5). Similarly, those for rainfall scenario R4, R5 and R6 were found.

(g) Based on the storm-based hit area calculated in Table D.4 and the adjusted number of natural terrain landslides calculated in Table D.5, the storm-based natural terrain landslide density was calculated in Table D.6 for rainfall scenario R1 to R6.

From the above, the storm-based rainfall-natural terrain landslide correlation was established. A comparison of the year-based natural terrain landslide density and the storm-based natural terrain landslide density is given in Figure 8.

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Table D.1 - Year-based Rainfall-Natural Terrain Landslide Correlation

Rainfall Scenario (Normalized Maximum Rolling 24-hour Rainfall in a Year)	Number of Natural Terrain Landslides on Natural Terrain Categorized* under the Rainfall Scenario from 1985 to 2000	Year-based Natural Terrain Area Categorized* under the Rainfall Scenario, km^2	Year-based Natural Terrain Landslide Density, No. / km^2 / year
R1 (0.00 - 0.10)	428	4940.1804	0.0866
R2 (> 0.10 - 0.15)	1579	3758.3471	0.4201
R3 (> 0.15 - 0.20)	1450	1276.5774	1.1358
R4 (> 0.20 - 0.25)	828	395.3534	2.0943
R5 (> 0.25 - 0.30)	497	92.4159	5.3779
R6 (> 0.30 - 0.35)	478	45.6045	10.4814

Note: * This refers to natural terrain that has the maximum rolling 24-hour rainfall in a year falling within the rainfall scenario's range of maximum rolling 24-hour rainfall.

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Table D.2 - Return Period and Annual Probability of Occurrence for Annual Rainfall Intensity At or Exceeding Specific Normalized Maximum Rolling 24-hour Rainfall

Normalized Maximum Rolling 24-hour Rainfall in a Year	Return Period, year	Probability of Occurrence for Rainfall At or Exceeding the Specific Normalized Maximum Rolling 24-hour Rainfall	Assessment of Probability of Occurrence for Rainfall Scenario	
			Rainfall Scenario	Annual Probability of Occurrence
0.10	1.7	0.4447	R1 (0.00 - 0.10)	0.5553
0.15	4.5	0.1993	R2 (> 0.10 - 0.15)	0.2454
0.20	15	0.0645	R3 (> 0.15 - 0.20)	0.1348
0.25	50	0.0198	R4 (> 0.20 - 0.25)	0.0447
0.30	180	0.0055	R5 (> 0.25 - 0.30)	0.0143
0.35	500	0.0020	R6 (> 0.30 - 0.35)	0.0035

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Table D.3 - Probability of Occurring Once or More for Different Rainfall Scenarios and Equivalent Return Period

Rainfall Scenario (Normalized Maximum Rolling 24-hour Rainfall in a Year)	Probability of Occurring Once or More	Equivalent Return Period, year
R1 (0.00 - 0.10)	0.5553	1.23
R2 (> 0.10 - 0.15)	0.2454	3.55
R3 (> 0.15 - 0.20)	0.1348	6.91
R4 (> 0.20 - 0.25)	0.0447	21.87
R5 (> 0.25 - 0.30)	0.0143	69.62
R6 (> 0.30 - 0.35)	0.0035	281.81

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Table D.4 - Conversion from Year-based Hit Area to Storm-based Hit Area

Rainfall Scenario (Return Period, year)	Year-based Natural Terrain Hit Area, km^2	Adjustment Factor for Conversion to Storm-based *	Storm-based Natural Terrain Hit Area, km^2
R1 (1.23)	4940.1804	1.4610	7217.5468
R2 (3.55)	3758.3471	1.1474	4312.5108
R3 (6.91)	1276.5774	1.0741	1371.1763
R4 (21.87)	395.3534	1.0230	404.4610
R5 (69.92)	92.4159	1.0072	93.0812
R6 (281.81)	45.6045	1.0018	45.6854

Notes: (1) Year-based Natural Terrain Hit Area refers to the total year-based area of natural terrain categorized under the relevant rainfall scenario from 1985 to 2000, as determined from spatial analysis.

(2) For *, see below.

* For R1 (Return Period = 1.23 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.813008	0.4435		
1	0.813008	0.3606	0.6480	0.6480
2	0.813008	0.1466	0.2634	0.5268
3	0.813008	0.0397	0.0714	0.2142
4	0.813008	0.0081	0.0145	0.0580
5	0.813008	0.0013	0.0024	0.0118
6	0.813008	0.0002	0.0003	0.0019
7	0.813008	0.0000	0.0000	0.0003
8	0.813008	0.0000	0.0000	0.0000
9	0.813008	0.0000	0.0000	0.0000
10	0.813008	0.0000	0.0000	0.0000
…		…		…
Total		0.5565		1.4610

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* For R2 (Return Period = 3.55 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.28169	0.7545		
1	0.28169	0.2125	0.8658	0.8658
2	0.28169	0.0299	0.1219	0.2439
3	0.28169	0.0028	0.0114	0.0343
4	0.28169	0.0002	0.0008	0.0032
5	0.28169	0.0000	0.0000	0.0002
6	0.28169	0.0000	0.0000	0.0000
7	0.28169	0.0000	0.0000	0.0000
8	0.28169	0.0000	0.0000	0.0000
9	0.28169	0.0000	0.0000	0.0000
10	0.28169	0.0000	0.0000	0.0000
…		…		…
Total		0.2455		1.1474

* For R3 (Return Period = 6.91 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.144718	0.8653		
1	0.144718	0.1252	0.9294	0.9294
2	0.144718	0.0091	0.0672	0.1345
3	0.144718	0.0004	0.0032	0.0097
4	0.144718	0.0000	0.0001	0.0005
5	0.144718	0.0000	0.0000	0.0000
6	0.144718	0.0000	0.0000	0.0000
7	0.144718	0.0000	0.0000	0.0000
8	0.144718	0.0000	0.0000	0.0000
9	0.144718	0.0000	0.0000	0.0000
10	0.144718	0.0000	0.0000	0.0000
…		…		…
Total		0.1347		1.0741

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* For R4 (Return Period = 21.87 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.045725	0.9553		
1	0.045725	0.0437	0.9773	0.9773
2	0.045725	0.0010	0.0223	0.0447
3	0.045725	0.0000	0.0003	0.0010
4	0.045725	0.0000	0.0000	0.0000
5	0.045725	0.0000	0.0000	0.0000
6	0.045725	0.0000	0.0000	0.0000
7	0.045725	0.0000	0.0000	0.0000
8	0.045725	0.0000	0.0000	0.0000
9	0.045725	0.0000	0.0000	0.0000
10	0.045725	0.0000	0.0000	0.0000
…		…		…
Total		0.0447		1.0230

* For R5 (Return Period = 69.62 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.014364	0.9857		
1	0.014364	0.0142	0.9928	0.9928
2	0.014364	0.0001	0.0071	0.0143
3	0.014364	0.0000	0.0000	0.0001
4	0.014364	0.0000	0.0000	0.0000
5	0.014364	0.0000	0.0000	0.0000
6	0.014364	0.0000	0.0000	0.0000
7	0.014364	0.0000	0.0000	0.0000
8	0.014364	0.0000	0.0000	0.0000
9	0.014364	0.0000	0.0000	0.0000
10	0.014364	0.0000	0.0000	0.0000
…		…		…
Total		0.0143		1.0072

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* For R6 (Return Period = 281.81 years)

X	ν	P(X)	% of Total P(X>=1)	Adjustment Factor for Conversion to Storm-based
0	0.003548	0.9965		
1	0.003548	0.0035	0.9982	0.9982
2	0.003548	0.0000	0.0018	0.0035
3	0.003548	0.0000	0.0000	0.0000
4	0.003548	0.0000	0.0000	0.0000
5	0.003548	0.0000	0.0000	0.0000
6	0.003548	0.0000	0.0000	0.0000
7	0.003548	0.0000	0.0000	0.0000
8	0.003548	0.0000	0.0000	0.0000
9	0.003548	0.0000	0.0000	0.0000
10	0.003548	0.0000	0.0000	0.0000
…		…		…
Total		0.0035		1.0018

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Table D.5 - Conversion from Year-based to Adjusted Number of Natural Terrain Landslides

Rainfall Scenario	Number of Natural Terrain Landslides on Natural Terrain Categorized under the Rainfall Scenario from 1985 to 2000, km^2	Theoretical Number of Natural Terrain Landslides that Would Have Occurred Due to the Natural Terrain Hit Once or More by Other Rainfall Scenarios						Adjusted Number of Natural Terrain Landslides
		R1	R2	R3	R4	R5	R6	
R1	428							428
R2	1579	181.1949						1397.8051
R3	1450	61.5455	131.6651					1256.7894
R4	828	19.0605	40.7764	60.5037				707.6593
R5	497	4.4555	9.5317	14.1431	8.6507			460.2191
R6	478	2.1987	4.7036	6.9792	4.2689	3.4976		456.3521

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Table D.6 - Storm-based Rainfall-Natural Terrain Landslide Correlation

Rainfall Scenario (Normalized Maximum Rolling 24-hour Rainfall in a Rainstorm)	Adjusted Number of Natural Terrain Landslides from Table D.5	Storm-based Natural Terrain Hit Area from Table D.4, km^2	Storm-based Natural Terrain Landslide Density, No. / km^2
R1 (0.00 - 0.10)	428	7217.5468	0.0593
R2 (> 0.10 - 0.15)	1397.8051	4312.5108	0.3241
R3 (> 0.15 - 0.20)	1256.7894	1371.1763	0.9166
R4 (> 0.20 - 0.25)	707.6593	404.4610	1.7496
R5 (> 0.25 - 0.30)	460.2191	93.0812	4.9443
R6 (> 0.30 - 0.35)	456.3521	45.6854	9.9890

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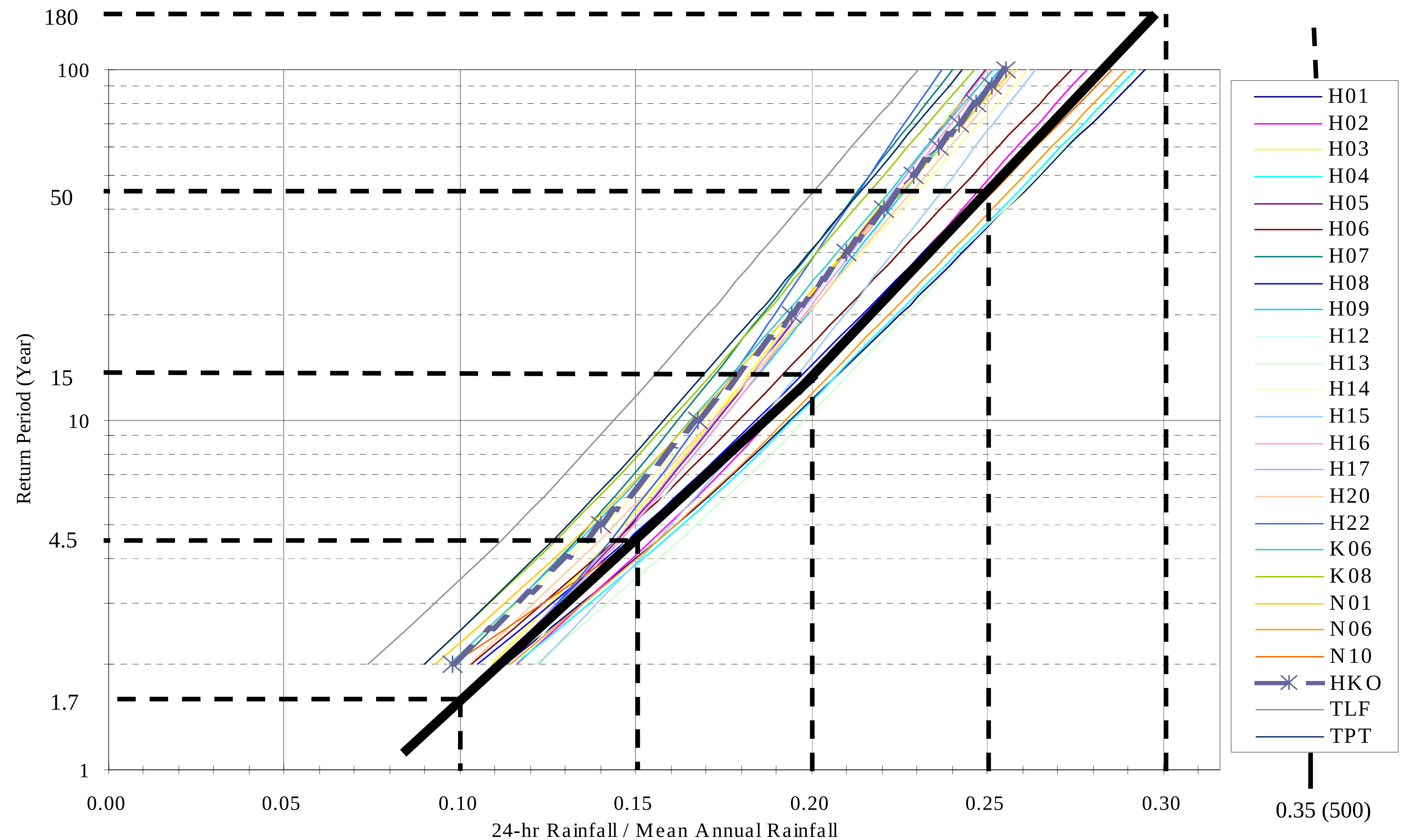

Note: (1) Data based on Evans et al (2001)

Figure D.1 - Return Periods of Normalised Maximum Rolling 24-hour Rainfall at Boundaries of R1 to R6

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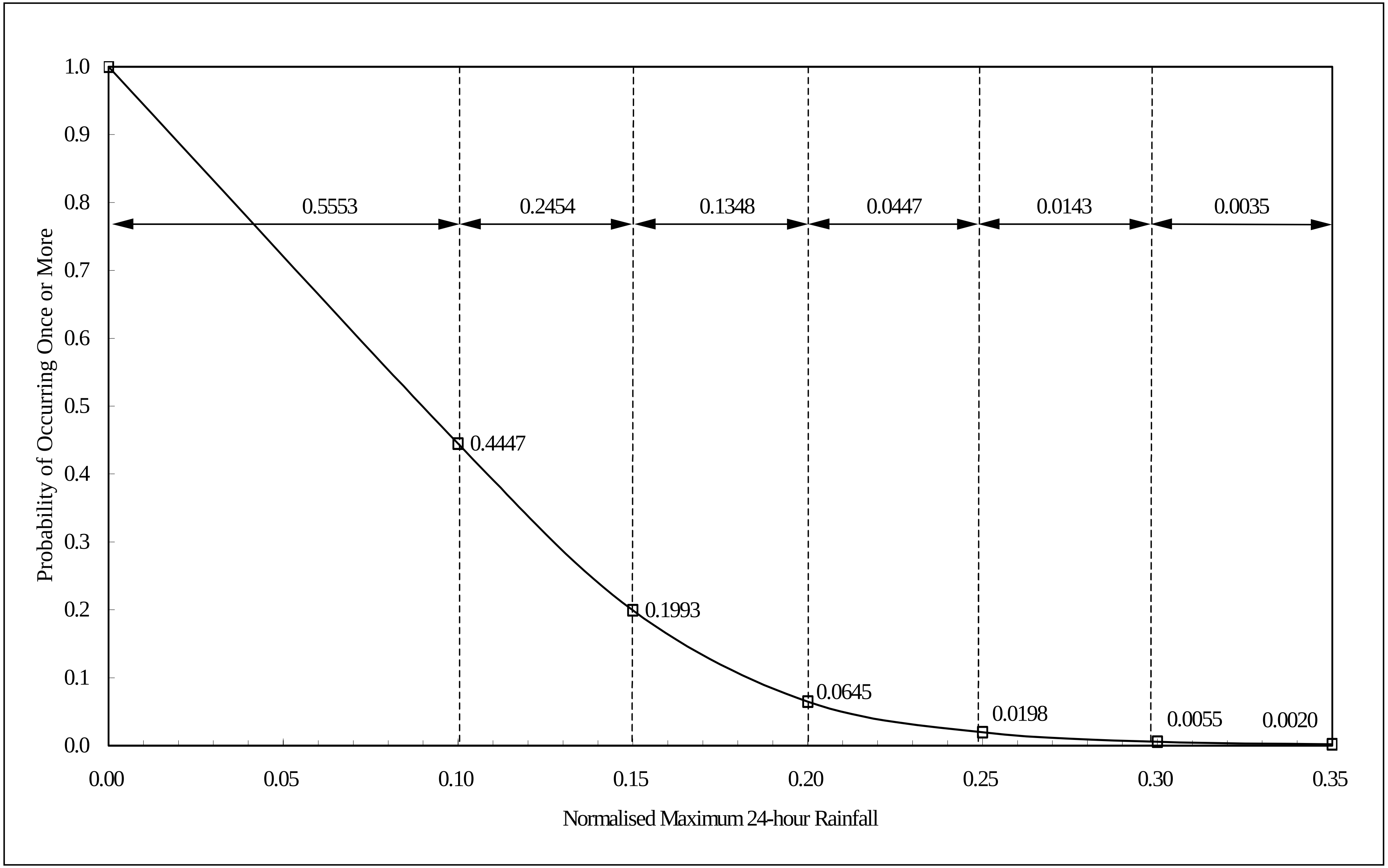

Figure D.2 - Probability of Occurring Once or More of Each Rainfall Class

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Geotechnical Manual for Slopes, 2nd Edition (1984), 300 p. (English Version), (Reprinted, 2000).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

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

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 2	Model Specification for Reinforced Fill Structures (1989), 135 p. (Reprinted, 1997).
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GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
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GEO Publication No. 1/96	Pile Design and Construction (1996), 348 p. (Reprinted, 2003).
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GEOLOGICAL PUBLICATIONS

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

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

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