EFFECTS OF CLIMATE CHANGE ON THE FREQUENCY OF SLOPE INSTABILITIES IN THE GEORGIA BASIN, BC - PHASE 1

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Cover Photo: Looking south over Wahleach/Jones Lake near Chilliwack, B.C.

These three debris slides occurred during a large storm event in November, 1990.

EXECUTIVE SUMMARY

Short duration rainfall intensities within Georgia Basin were successfully correlated with average annual precipitation. As indicated below, correlation coefficients increase with rainfall duration and decrease with increasing return period.

RAINFALL–INTENSITY–DURATION		r^2 VALUE FOR BEST FIT RELATIONSHIP WITH ANNUAL PRECIPITATION FOR A RETURN PERIOD OF:					
MINUTES	HOURS	2 years	5 years	10 years	25 years	50 years	100 years
5		0.53	0.41	0.33	0.26	0.23	0.20
10		0.56	0.36	0.26	0.18	0.13	0.10
15		0.59	0.40	0.30	0.21	0.17	0.13
30		0.69	0.53	0.42	0.32	0.26	0.22
	1	0.81	0.68	0.61	0.53	0.46	0.44
	2	0.90	0.84	0.79	0.72	0.69	0.65
	6	0.91	0.90	0.88	0.86	0.84	0.83
	12	0.91	0.89	0.86	0.85	0.84	0.83
	24	0.92	0.88	0.87	0.84	0.82	0.81

The developed regression equations provide a basis for estimating rainfall intensities in areas without IDF data.

The developed relationships between rainfall intensity and annual precipitation were used to determine how increasing annual precipitation due to climate change could affect the frequency of slope instability. This analysis has been undertaken principally on rainfall–intensity–duration criteria prepared by *Caine (1980)*.

DURATION (hrs)	RAINFALL INTENSITY (mm/hr) REQUIRED FOR INITIATION
	CAINE (1980) Shallow Landslides & Debris Flows
0.25	25.4
1	14.8
2	11.3
6	7.4
12	5.6
24	4.3

Similar analyses were attempted using alternative criteria proposed by *Innes (1983)* but this was abandoned as these rainfall intensities had return periods which were smaller than those which can be calculated using the Meteorological Service of Canada rainfall–intensity–frequency duration analytical routines.

Our analyses indicate that climate change related increases in annual precipitation totals will increase rainfall intensities of $\leq$24-hours. This is predicted to result in an increase in the frequency of slope instabilities. The effects will increase with increasing annual precipitation. The effects on slope instabilities will also vary with rainfall duration and the climatalogical setting (as indicated by presently occurring annual precipitation totals). Assuming a 10% increase in average annual precipitation occurs over the next 80 years, it is expected that the average return period between 24-hour rainfall events which are large enough to initiate slope failures could decrease from 10.4 to 6.3 years in locations which presently have average annual precipitation totals of 1,000 to 1,500 mm.

The analyses in this report provide an initial method of identifying those areas where climate change could have the largest impact on slope instability. The study results indicate that future land management practices should include measures to reduce the potential for slope instability due to increasing precipitation.

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TABLE OF CONTENTS

Page
Executive Summary i
Acknowledgements ii
Table of Contents iii
List of Figures iv
List of Tables iv
List of Addendums v
Statement of Limitations of Report v

1: INTRODUCTION AND OBJECTIVES 1

2: STUDY METHODOLOGY 2

3: PRECIPITATION DATA 3

4: EFFECT OF CLIMATE CHANGE ON PRECIPITATION 4

5: RELATIONSHIP BETWEEN AVERAGE ANNUAL PRECIPITATION AND SHORT DURATION RAINFALL INTENSITIES 5

6: RAINFALL INTENSITY CRITERIA FOR INITIATION OF SHALLOW LANDSLIDES OR DEBRIS FLOWS 6

7: COMPARISON OF 2-YEAR RETURN PERIOD RAINFALL INTENSITIES TO CAINE’S AND INNES’ INITIATION CRITERIA
7.1 Caine’s Criteria 7
7.2 Innes’ Criteria 7

8: EFFECTS OF INCREASING ANNUAL PRECIPITATION ON THE PREDICTED FREQUENCY OF SHALLOW LANDSLIDES AND DEBRIS FLOW EVENTS
8.1 Data Analysis 8
8.2 Results
  8.2.1 Caine’s Criteria for Initiation of Shallow Landslides or Debris Flows .. 8
  8.2.2 Innes’ criteria for Initiation of Shallow Landslides or Debris Flow .. 10

9: CONCLUSIONS AND DISCUSSION 10

10: SOURCES OF INFORMATION
10.1 References 12
10.2 Personal Communications 13

LIST OF FIGURES

Page
1.1 Georgia Basin location map F-1
4.1 Predicted percentage change in average monthly precipitation based on GCMII F-2
4.2 Predicted percentage change in average monthly precipitation based on CGCMI F-2
5.1 Examples of developed relationships between rainfall intensity and average annual precipitation F-3

LIST OF TABLES

3.1 List of climate stations used in this study, sorted by average annual precipitation T-1
4.1 Comparison of changes in precipitation predicted by the GCMII & CGCMI models T-2
5.1 Correlation coefficients for best fit relationships between rainfall intensity and average annual precipitation T-3
5.2 Best-fit equations to estimate 5 to 30 minute rainfall intensities on the basis of average annual precipitation T-4
5.3 Best-fit equations to estimate 1 to 24 hour rainfall intensities on the basis of average annual precipitation T-5
7.1 Comparison of 2-year return period rainfall intensities with Caine’s criteria for slope instability T-6
7.2 Comparison of 2-year return period rainfall intensities with Innes’ criteria for slope instability T-7
8.2.1 Predicted frequency of exceeding Caine's instability criterion based on the present precipitation regime T-8
8.2.2 Predicted frequency of exceeding Caine's instability criterion based on a 5% increase in annual precipitation T-9
8.2.3 Predicted frequency of exceeding Caine's instability criterion based on a 10% increase in annual precipitation T-10
8.2.4 Predicted frequency of exceeding Caine's instability criterion based on a 20% increase in annual precipitation T-11
8.2.5 Predicted frequency of exceeding Caine's instability criterion based on a 30% increase in annual precipitation T-12
8.2.6 Increase in the frequency of exceeding Caine’s slope instability criterion due to a 5% increase in average annual precipitation T-13
8.2.7 Increase in the frequency of exceeding Caine’s slope instability criterion due to a 10% increase in average annual precipitation T-14
8.2.8 Increase in the frequency of exceeding Caine’s slope instability criterion due to a 20% increase in average annual precipitation T-15
8.2.9 Increase in the frequency of exceeding Caine’s slope instability criterion due to a 30% increase in average annual precipitation T-16

LIST OF ADDENDUMS

1: Appendix 1: Summary of annual precipitation and rainfall intensity data
Appendix 3: Predicted rainfall intensities based on relationships between rainfall intensity and average annual precipitation
Appendix 4: Predicted rainfall intensity–duration–frequency data for 29 representative stations
Appendix 8: Probability of exceeding Caine's or Innes' rainfall frequency criteria for slope instability as a function of existing or augmented annual precipitation totals

2: Appendix 2: Relationship between short duration rainfall intensity and average annual precipitation
Appendix 5: Predicted rainfall intensity–duration–frequency graphs for 29 selected climate stations
Appendix 6: Probability of exceeding Caine's rainfall intensity criteria for slope instability as a function of average annual precipitation
Appendix 7: Probability of exceeding Innes' rainfall intensity criteria for slope instability as a function of average annual precipitation

STATEMENT OF LIMITATIONS OF REPORT

This report was prepared by M. Miles and Associates Ltd. (MMA) for use by the Meteorological Service of Canada. Conclusions in this report reflect the judgement of MMA staff in light of the information available to MMA at the time of report preparation.

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EFFECTS OF CLIMATE CHANGE ON THE FREQUENCY OF SLOPE INSTABILITIES IN THE GEORGIA BASIN, B.C. – PHASE 1

1: INTRODUCTION AND OBJECTIVES

Shallow landslides and debris flows are a common form of slope instability within the Georgia Basin *(Figure 1.1)*. These events can result in direct economic loss by destroying infrastructure such as roads, bridges, housing, etc., or degrading the productivity of the forestry land base. Stream channel morphology or stability, and fisheries habitat, can also be affected if the sediment produced by such events enters a water course.

Shallow landslides or debris flows are commonly initiated as a result of intense rainfall or a combination of moderately intense rainfall or snowmelt, particularly if they occur during wet antecedent ground conditions. Climate model studies indicate that increasing CO_2 concentrations will increase annual precipitation totals within the Georgia Basin *(e.g. Taylor and Langlois, 2000)*. Studies by *Stone* et al. *(2000)* suggest that climate change could also result in more extreme precipitation events. This in turn could result in an increased frequency of slope instability.

There is, as yet, little reliable information on how climate change will affect rainfall intensities within the Georgia Basin study area. However, if this information was available, it would allow published rainfall intensity slope initiation criteria to be used to quantify how climate change might affect the frequency of these events.

Previous studies by *Loukas and Quick (1995)* have determined that rates of 24-hour rainfall intensity can be correlated with average annual precipitation in southwestern BC. The initial objective of the present study was to determine if shorter duration rainfall intensities could be correlated with annual precipitation. Our results indicate that this was possible with the relationships being more robust for longer duration events (i.e. 2 to 24 hour) and shorter return periods (i.e. 2 to 25 years). The developed relationships were used to estimate how increases in annual precipitation predicted by the Global Circulation Model II and the Coupled Global Circulation Model 1 might affect rainfall intensities. This allows the frequency of slope instability events predicted on the basis of existing and future rates of short-duration rainfall to be compared based on previously developed initiation criteria.

The following report describes the results of these investigations.

2: STUDY METHODOLOGY

The study was undertaken as a cooperative effort with the Meteorological Service of Canada (MSC). The initial partner was Mr. Eric Taylor. Messrs. Paul Whitfield, Reg Dunkley and Bruce Thompson of MSC all assisted in various stages of the project and particularly after Mr. Eric Taylor left MSC to work with Natural Resources Canada in Ottawa.

MSC's principal responsibility was to provide annual precipitation and short duration rainfall intensity data from climate stations in or near the Canadian portion of the Georgia Basin *(see Figure 1.1)*. This task was complicated by recent changes in computers, operating systems and software which prevented undertaking some of the desired data extractions or analyses. Specifically, rainfall intensity–duration–frequency analyses could not be run on monthly data and rainfall intensities for less than 2-year return periods could not be calculated.

The analyses undertaken during this project can be summarized as follows:

1: Rainfall intensity–duration–frequency analyses (IDF) and average annual precipitation values were obtained for MSC climate stations with ≥10 years of IDF and annual precipitation data.

2: The relationship between predicted 5-minute to 24-hour rainfall intensities (for various return periods) and annual precipitation were determined.

3: The results of recent climate models were reviewed to determine how climate change is expected to influence annual precipitation.

4: The developed relationships between rainfall intensity and annual precipitation were used to estimate how predicted changes in annual precipitation would affect short duration rainfall intensities; and

5: Rainfall intensity–duration threshold criteria developed by *Caine (1980)* and *Innes (1983)* were used to assess how changes in rainfall intensity will affect the frequency of shallow slope instabilities or debris flows.

During the course of this study it became apparent that monthly precipitation totals during the winter period (when slope instabilities most frequently occur) were expected to increase more than the annual precipitation. In addition, initial data analyses determined that Caine's and, to a greater extent, Innes' criteria for initiation of slope instability were less than the two-year return period rainfall intensities at some stations. It would have been desirable to modify the initially proposed study plan (outlined above) to examine the effect of predicted changes in monthly precipitation totals. This would require determining the relationship between average monthly precipitation and monthly rainfall IDF statistics. In addition, it would have been desirable to re-compute MSC's rainfall IDF data and include intensity estimates for return periods of less than two years. These objectives were discussed with the MSC study team (listed above). It was decided that these additional analyses should be undertaken in the future when funding was available to make the required software revisions. As a consequence, the present report is based on the originally proposed analysis of annual precipitation statistics.

The study methodology assumes that:

1: Relationships between short duration rainfall and annual precipitation totals derived from regional climate data can be used to assess how future changes in annual precipitation might affect rainfall intensities at a single location; and

2: Published rainfall intensity–duration criteria can be used to predict the frequency of slope instability events under both contemporary and future climatic conditions.

These assumptions may not be valid. It is expected that increasing winter precipitation will result in wetter antecedent soil moisture conditions, which, alone, could result in an increased frequency of slope instability events. Climate change also has the potential to affect forest cover *(e.g. Joyce et al., 2000)* or other factors which affect slope stability. This study is, therefore, limited in scope as it only addresses one aspect of a complicated, multifaceted process. The project results do, however, provide one method of estimating how changing climate might affect slope stability within the Canadian section of the Georgia Basin.

3: PRECIPITATION DATA

The MSC Climate Station Catalogue was reviewed and stations which had ten or more years of both annual precipitation and rainfall IDF data were identified. A total of 49 stations met these criteria *(Table 3.1)*. Most of the selected stations are located within the Canadian section of the Georgia Basin *(Figure 1.1)*, however, data from a few additional Canadian sites in nearby areas were also included to increase the sample size and the range of annual precipitation values. One important limitation of the data is the generally low elevation of reporting stations. Elevations range between 1 and 381 m asl; the median elevation is 32 m and only 6 stations exceed 150 m in elevation.

The MSC's standard IDF data analyses were obtained, based on information up to 1998. These summaries predict the rainfall intensities which are expected to occur for return periods of 2, 5,20, 25, 50 and 100 years. Where the data is available, estimates are provided for durations of 5, 10, 15 and 30 minutes and 1, 2, 5, 12 and 24 hours. The calculations are undertaken using the annual maximum rainfall intensity value observed in each year of record. Return period estimates are based on the Gumbel distribution fitted by the Method of Moments *(see Hogg and Carr, 1985)*.

Average annual precipitation data were similarly obtained from the MSC for all climate stations with IDF data. The average annual precipitaiton totals were based on the period of record which, in many cases, is longer than the period of rainfall intensity data. As discussed in *Whitfield and Taylor (1998)*, the annual precipitation regime in coastal BC has changed over time. Using the full period of record could therefore result in some bias in the analysis. However, this was not felt to be significant in the context of the present study objectives.

The MSC generally performs IDF analyses based on the January 1 to December 31 calendar year data extractions. However, MSC decided to adopt a "rain year" (defined as July 1 to June 30) for some westcoast areas (specifically basins 101, 102, 103 and 110, *Dnes, pers. comm.*) Our data includes stations in these basins, plus some stations in basins 104 and 111 *(see Table 3.1)*. There is, therefore, some inconsistency in the MSC data analysis, but this is again not felt to be a significant problem.

4: EFFECT OF CLIMATE CHANGE ON PRECIPITATION

During the initial stages of the project, the Global Circulation Model II (GCMII) provided the best available projections of the future precipitation regime in the Georgia Basin (see http://www,ccma.bc.ec.ca/diagnostics/gcm2.html, accessed on October 24, 2000). A doubling of the atmospheric CO_2 concentrations by the middle of the 21st century was predicted to increase annual precipitation by 13%. Monthly values were predicted to be more variable, with large increases in the winter months and decreases in the summer months being expected. As illustrated on *Figure 4.1*, the GCMII model calculates that precipitation could increase in the winter by up to 40% in December and 60% in January. Summer precipitation is predicted to decrease with May values being 30% smaller than present *(see Figure 4.1)*.

The results of the Coupled Global Circulation Model 1 (CGCM1) became available during the latter part of this study (see http://www.cics.uvic.ca/scenarios/index.cgi accessed on October 24, 2000). Annual precipitation totals are projected to increase by 2% in 2020, 5% in 2050 and 10% in 2080, in comparison to the 1961 to 1990 period. As indicated on *Table 4.1* and *Figure 4.2*, the predicted changes in average monthly precipitation are more modest in comparison to those predicted by GCMII. For example, the maximum fall or winter increase in monthly precipitation is predicted to occur in September and range between 17 to 21% over the period between 2020 to 2080. January precipitation is expected to increase between 7 and 20%, rather than the 60% increase predicted by the GCMII calculations. The maximum reduction is again projected to occur in May with values being 19 to 31% smaller than present.

Given the lack of agreement between the two models (particularly for winter and annual precipitation totals), and the potential for future model refinements, the study team decided to evaluate the potential slope stability effects of increasing annual precipitation totals by 5, 10, 20 and 30%. This should allow the significance of future model predictions to be readily assessed. The CGCMI data suggests that a 10% increase in annual precipitation is presently the most likely future scenario.

5: RELATIONSHIP BETWEEN AVERAGE ANNUAL PRECIPITATION AND SHORT DURATION RAINFALL INTENSITIES

The relationship between average annual precipitation and rainfall intensity was determined using the program *TableCurve2D (SPSS 1996)*. This sophisticated curve fitting routine generates best fit relations using a wide variety of equations. The predicted equations were selected on the basis of both coefficient of determination (or r^2) values and a visual inspection of how well the equation fit the data *(e.g. Figure 5.1)*. All the results are compiled in APPENDIX 2 [ADDENDUM 2]

The coefficient of determination values of the best fit equations are summarized on *Table 5.1*. The developed equations between average annual precipitation and rainfall intensity are listed on *Tables 5.2* and *5.3*. The robustness of the relationships between rainfall intensity and annual precipitation show a well defined pattern. Examination of *Table 5.1* indicates that r^2 values increase with increasing rainfall duration and decrease with increasing return period. Both these trends are expected. Rainfall durations of less than approximately half an hour are commonly associated with convective processes and are comparatively poorly correlated with annual precipitation (r^2 values are typically <0.5 for ≥ 5-year return period events). In contrast, rainfall events of greater than half an hour in duration have r^2 values ranging from 0.69 to 0.92 for a 2-year return period. This suggests that both annual precipitation and longer term rainfall intensities are strongly influenced by orographic effects.

The compiled statistics indicate that r^2 values decrease with increasing return period. This likely reflects:

i) the increasing uncertainty in longer return period rainfall intensities due to the frequently short period of record;

ii) the effects of the unequal record lengths in the annual precipitation and rainfall intensity data; and

iii) the possibly increased importance of cyclonic or other non-orographic processes during higher return period events.

Despite these limitations, the computed correlations provide an adequate basis for an initial estimate of how increasing annual precipitation might affect rainfall intensity. The reliability of the developed equation will, however, decrease with both decreasing duration and increasing return period.

6: RAINFALL INTENSITY CRITERIA FOR INITIATION OF SHALLOW LANDSLIDES OR DEBRIS FLOWS

Shallow landslides are defined as shallow planar failures, typically less than 2 to 3 m deep. Debris flows are a type of sub-aerial landslide that involves water saturated, predominantly coarse grained, inorganic and organic material which rapidly flows down a slope or a pre-existing channel *(see Varnes, 1978; Pierson and Costa, 1987; VanDine, 2000)*

Shallow landslides or debris flows can be initiated by a range of precipitation and snowmelt conditions *(Bovis, 1993)*. Short-duration intense rainfall is commonly used as an initiation criterion, even though studies such as *Church and Miles (1987)* or *Hogan and Schwab (1991)* have shown that snowmelt and antecedent soil moisture can significantly affect the amount of precipitation required to trigger an event. Despite these limitations, two widely used rainfall intensity criteria for the initiation of shallow landslides or debris flows have been used in this study to assess the effects of climate change on slope instability.

Caine (1980) compiled rainfall intensity–duration data from shallow landslides and debris flows located in many different geologic and topographic (mostly mountainous) environments on relatively undisturbed slopes. These analyses indicate that, within these environments, the limiting threshold for initiating this type of slope failure is predicted by the following relationship:

$$I = 14.82D^{-0.39}$$

where I is rainfall intensity (mm/hr.) and D is rainfall duration (hrs.) The equation is best defined for rainfall durations between 10 minutes and 10 days.

Innes (1983) undertook a similar study which only considered data for debris flows. His results, when transposed to the same form as Caine's equation, indicate that the threshold criterion is as follows:

$$I = 0.0126 + 4.9176D^{0.4977}$$

As indicated on the table below, Innes' analysis predicts that debris flows can be initiated by lower rainfall–intensities than those predicted by Caine's Criteria.

DURATION (hrs)	RAINFALL INTENSITY (mm/hr) REQUIRED FOR INITIATION	
	CAINE (1980) **Shallow Landslides & Debris Flows**	**INNES (1983)** **Debris Flows**
0.25	25.4	9.8
1	14.8	4.9
2	11.3	3.5
6	7.4	2.0
12	5.6	1.4
24	4.3	1.0

The study by *Church and Miles (1987)*, found that shallow landslides or debris torrents (representing a wetter form of debris flow which are typically channelized along drainage courses) occur in the Georgia Basin in association with rainfall–intensity–duration combinations which are smaller than those predicted by Caine's Criterion. This may reflect the effect of slope disturbance, discrepancies between observed valley bottom precipitation intensities and those occurring in the typically higher elevation initiation areas, the presence of unmeasured local high intensity rainfall cells and the previously-discussed effects of antecedent soil moisture or snowmelt.

7: COMPARISON OF 2-YEAR RETURN PERIOD RAINFALL INTENSITIES TO CAINE'S AND INNES'S INITIATION CRITERIA

7.1 CAINE'S CRITERIA

Two-year return period rainfall intensities at all the selected climate stations are compiled on *Table 7.1*. Caine's *(1980)* criteria for the initiation of shallow landslides or debris flows are also tabulated to identify sites where the 2-year return period rainfall intensities exceed Caine's thresholds. [These values are shaded on *Table 7.1*.] This analysis indicates that 2-year return period rainfall intensities commonly exceed Caine's criteria, particularly for events of ≤ 15 minutes duration or for longer duration events at sites with average annual precipitation values which exceed 2,000 mm.

This result indicates that we need to determine the relationship between average annual precipitation and rainfall intensities with return periods of less than 2-years to thoroughly assess the effect of changing annual precipitation on slope stability. As previously discussed, the MSC rainfall IDF program results do not provide this information. As will be discussed in SECTION 8.2, this reduces our ability to accurately define the return period for exceeding Caine's criteria at some locations.

7.2 INNES' CRITERIA

Observed two-year return period rainfall intensities are summarized on *Table 7.2*, along with *Innes' (1983)* criteria for the initiation of debris flows. This analysis indicates that 2-year return period rainfall intensities consistently exceed these criteria at all stations. As a result, the MSC data analysis is not able to reliably predict the return period of events which exceed Innes' Criteria. This topic will be revisited in SECTION 8.3.

8: EFFECTS OF INCREASING ANNUAL PRECIPITATION ON THE PREDICTED FREQUENCY OF SHALLOW LANDSLIDES AND DEBRIS FLOW EVENTS

8.1 DATA ANALYSIS

The relationships between rainfall intensity and average annual precipitation developed in SECTION 5 have been used to estimate how rainfall intensities would increase with increasing average annual precipitation. These calculations have been undertaken based on the contemporary average annual precipitation and 5, 10, 20 and 30% increases in this value. This information is presented in APPENDIX 3 [ADDENDUM 1].

A series of steps were then undertaken to determine how the increased rainfall intensities associated with increased annual precipitation totals would affect the frequency of slope failures based on Caine's and Innes' instability criteria:

i) A sub-set of 29 sites, which spanned the range of annual precipitation values encountered in this study, were selected [see APPENDIX 4 in ADDENDUM 1];

ii) The return period and rainfall intensity estimates predicted in APPENDIX 3 were plotted for 5-minute to 24-hour durations for each of the selected sites. Best fit relationships were derived using the TableCurve2D curve fitting software [see APPENDIX 5 in ADDENDUM 2];

iii) The return period at which Caine's and Innes's criteria for slope instability were exceeded were determined for each site; and

iv) The calculated return period for exceeding Caine's and Innes's instability criteria were then plotted against the average annual precipitation at each of the selected sites. These analyses, which are compiled in Appendices 6 and 7 [see Addendum 2], provide a simple method of estimating the average return period for exceeding Caine's or Innes' instability criteria based on average annual precipitation totals.

8.2 RESULTS

8.2.1 Caine's Criteria for Initiation of Shallow Landslides or Debris Flows

The developed relationships between the frequency of exceeding Caine's landslide initiation criteria and average annual precipitation [see APPENDIX 6 in ADDENDUM 2] were used to determine the effect of increasing average annual precipitation by 5, 10, 20 and 30%. These results, which are compiled in APPENDIX 8 [ADDENDUM 1], indicate that the predicted average return period for slope instability initiation is strongly correlated with the annual precipitation total. *Table 8.2.1* shows the predicted average return period for exceeding Caine's criteria under the present precipitation regime. Average return periods decrease with increasing average annual precipitation totals and increase with increasing durations. For example at dry sites with annual precipitation totals of 300 to 1,000 mm, the average return period for exceeding Caine's criteria increases from 5.74 years for a 5-minute duration to >2,200 years for a 24-hour period. This implies that slope instabilities are most likely to be caused by short duration events. In contrast, at wetter sites having annual precipitation totals of 1,500 to 2,000 mm, the frequency of failure varies from 2 years for a 5-minute duration event to 10-years for a period of 24 hours. At the wettest sites, with annual precipitation totals of 3,000 to 3,700 mm, the predicted frequency of failure varies from 1.0 years at 5-minute durations to 0.5 years for a 24-hour period. The magnitude of these variations is unexpected and additional analyses of field data on the frequency of rainfall-induced slope instabilities in the Georgia Basin are required to determine if the predicted systematic variation in failure frequencies are reasonable.

The predicted frequency of exceeding Caine's instability criteria, based on 5, 10, 20 and 30 percent increases in average annual precipitation totals are presented on *Tables 8.2.2 to 8.2.5*, respectively. These compilations indicate that increasing annual precipitation totals will result in a greater frequency of exceeding Caine's slope instability criteria.

In order to calculate the percentage increase in the frequency of exceeding Caine's criteria, the return period estimates on *Tables 8.2.2 to 8.2.5* have been converted to frequency of exceedance (1/x times 100), the two values have been divided, and the result multiplied by 100 to yield comparative values in percent. The results are shown on *Figures 8.2.6 to 8.2.9*. These analyses indicate that the increase in the frequency of exceeding Caine's criteria varies with both duration and present annual precipitation total. For example, *Table 8.2.6* indicates that increasing the annual precipitation total by 5% results in a 101 to 132% increase in the frequency of exceeding Caine's criteria. The maximum increase occurs for 6-hour events at sites which presently have 3,000 to 3,700 mm of annual precipitation. The minimum increase occurs as a result of changes in short duration rainfall intensity at sites with comparatively small average annual precipitation totals.

A 30% increase in average annual precipitation is predicted to increase the frequency of slope failures by 111 to 448%. Maximum increases again occur at a duration of 6 hours at sites presently having 3,000 to 3,700 mm of precipitation. Slide frequency is also predicted to increase by 403% over 24-hour durations in areas having 1,000 to 1,500 mm of annual precipitation.

As discussed in SECTION 4, a 10% increase in annual precipitation appears to be the most probable climate change scenario over the next 80 years. As indicated on *Table 8.2.6*, this would result in a 101 to 132% increase in the frequency of exceeding Caine's criteria. The maximum increase again occurs for a 6 hour duration in areas of 3,000 to 3,700 mm of annual precipitation.

The interpretation provided above is limited in that it does not consider the actual change in the predicted return period for slope stability initiation. Inspection of *Tables 8.2.1 to 8.2.5* indicates that the average return period between slope instabilities at sites which presently have 3,000 to 3,700 mm of annual precipitation is typically smaller than 1.3 years. This seems unreasonably frequent. In addition, there may be little real significance in reducing the predicted return period from, for example, 1.0 to 0.7 years. Similarly for very dry sites, decreasing the predicted average return period from 2,200 to 1,078 years may also have little practical significance. In contrast, for areas with more typical annual precipitation total of 1,500 to 2,000 mm, the predicted changes in slope stability could be much more significant. For example, for durations of 24 hours the predicted average period between slope stability initiation is predicted to decrease from 10.4 years under the present precipitation regime to 4.1 years with a 30% increase in annual precipitation.

A 10% increase in precipitation is expected to result in an average exceedance period of 6.3 years which is a 165% increase in the predicted frequency of slope failures in comparison to present conditions. These effects could cause significant damage if they actually resulted in a corresponding increase in slope failures.

8.2.2 Innes' Criteria for Initiation of Shallow Landslides or Debris Flows

As discussed in SECTION 7.2, the two-year return period rainfall intensities at all stations exceed Innes' Criteria. As a consequence the relationships between failure frequency and average annual precipitation [compiled in APPENDIX 7, ADDENDUM 2] becomes poorly defined for duration ≥1 hour. This results from an inability to reliably extrapolate low return period rainfall intensity on the intensity–duration–frequency graphs presented in APPENDIX 5. As a consequence, the frequency of exceeding Caine's Criteria cannot be reliably calculated on the basis of the available data. For this reason, no further analyses of Innes' Criteria can be undertaken.

9: CONCLUSIONS AND DISCUSSION

This analysis indicates that short duration rainfall intensities of ≥~1 hour duration can be reasonably well predicted on the basis of average annual precipitation. These results provide a practical method of estimating IDF data in areas where this information is not available.

The potential effect of varying rainfall intensities on slope stability has been investigated on the basis of Caine's criteria. The frequency of exceeding these criteria has been shown to vary substantially under the present precipitation regime. The average return period between failures has been calculated to decrease with increasing annual precipitation (under the present discharge regime). Additional analysis is required to determine if this conclusion is supported by field information.

The developed relationships indicate that increasing annual precipitation totals due to climate change will result in increased rainfall intensities and an increased frequency of rainfall events which exceed Caine's criteria for initiation of slope instability. The potential increase in the frequency of slope instabilities is shown to vary with both rainfall duration and the annual precipitation total. As a consequence, comparison of pre- and post-climate change slope stability cannot be described by a single comparative frequency statistic. Increasing average annual precipitation by 10% within areas which currently have average annual precipitation values of 1,000 to 1,500 mm is predicted to result in a 110 to 165% increase in the frequency of exceeding Caine's slope initiation criteria. For a duration of 24-hours this would decrease the predicted average return periods between failure from 10.4 to 6.3 years. This effect could result in a significant increase in the risk of damage to property or the land base. As a consequence, it would be prudent to incorporate measures which reduce the potential for slope instability into future land use strategies or undertake remedial measures where warranted, *(e.g. Chatwin, et al., 1994; Atkins, et al., 2000)*. The results of this analysis would assist in determining in which climatic sub-zones these efforts would be most beneficial.

The analyses in this report could be improved through a variety of additional analyses. As discussed in SECTION 4, it is predicted that climate change will preferentially increase monthly precipitation totals in the winter. It would, therefore, be desirable to undertake similar analyses based on monthly precipitation totals and associated IDF data. The analytical software employed by the MSC could also be modified such that rainfall intensities of < 2-year return periods could be calculated. This would allow a similar investigation of *Innes (1983)* debris flow initiation criteria. Finally, and likely most importantly, results of the present calculations predict that the frequency of slope instabilities will vary regionally as a function of average annual precipitation. Field work is needed to determine how factors such a vegetation cover, soil weathering, sediment availability or land use affect the empirically derived initiation criteria used as a basis for making these predictions.

10: SOURCES OF INFORMATION

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10.2 PERSONAL COMMUNICATIONS

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Figure 1.1: Georgia Basin location map
(*from http://www.pyr.ec.gc.ca/GeorgiaBasin/images/maps/GB_PS_Map.jpg*)

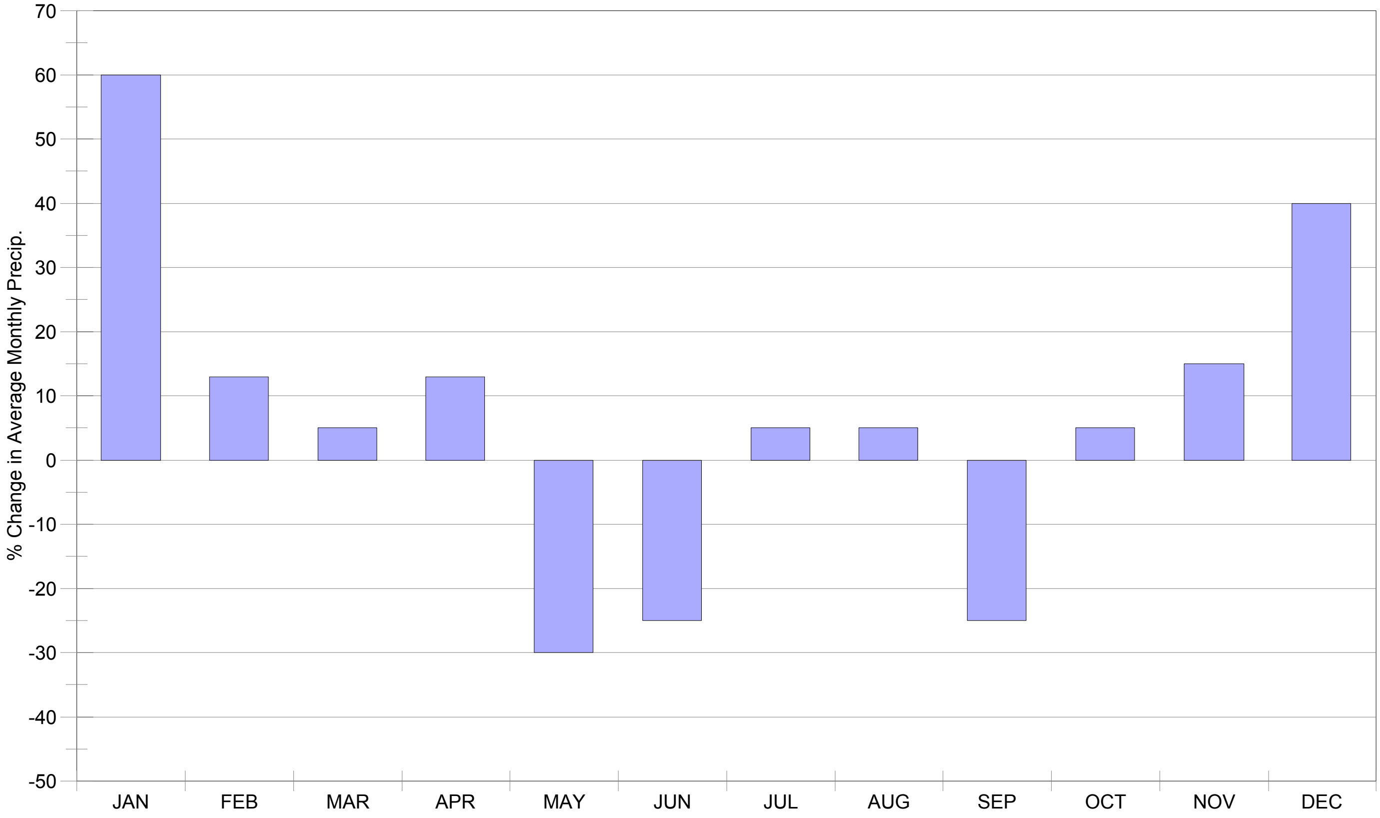


Figure 4.1: Predicted percentage change in average monthly precipitation based on GCMII

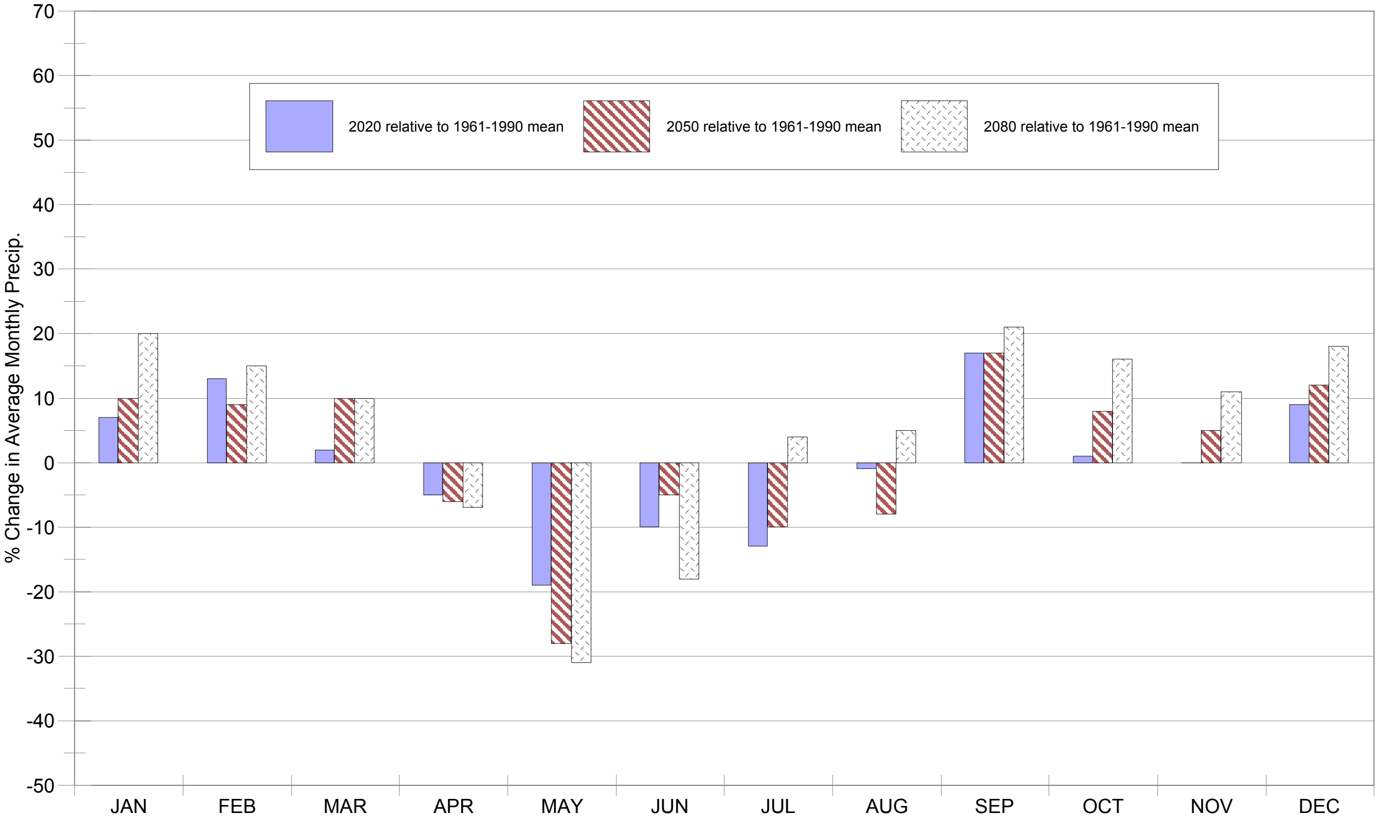
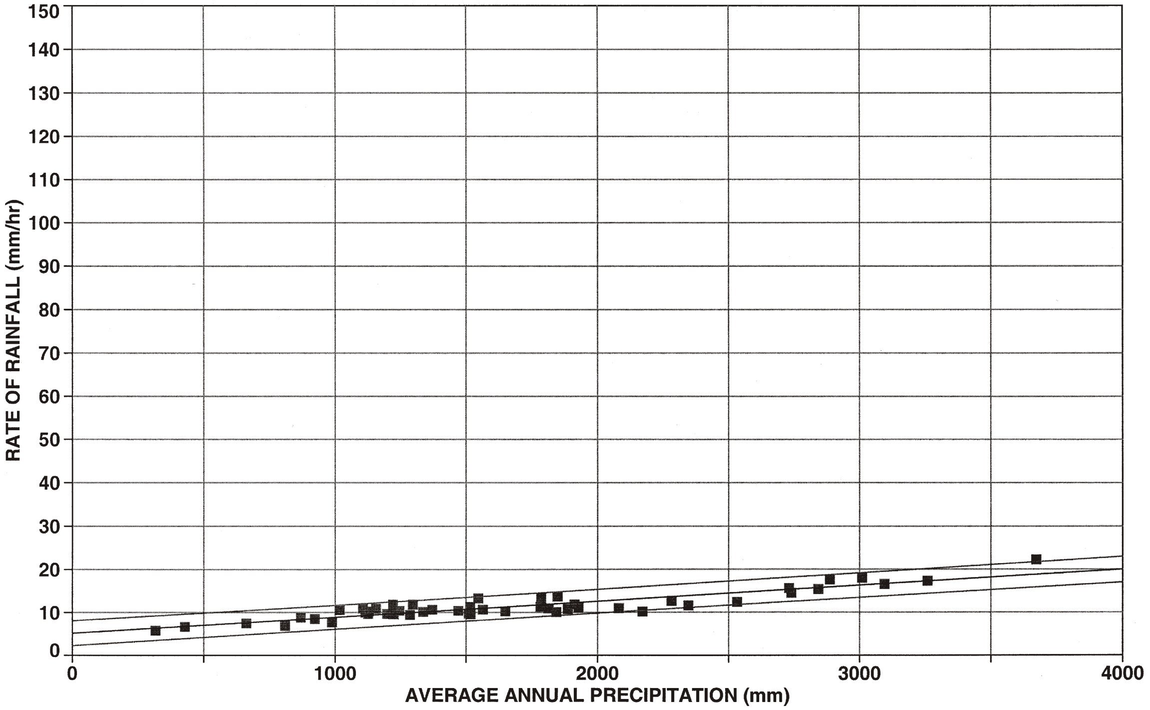


Figure 4.2: Predicted percentage change in average monthly precipitation based on CGCMI

1 HOUR DURATION : 2-YEAR RETURN PERIOD
Rank 30 Eqn 1 $y=a+bx$
$r^2=0.8155718$ DF Adj $r^2=0.80755318$ FitStdErr=1.3603466 Fstat=207.84172
$a=5.178127$
$b=0.0037149161$



24 HOUR DURATION : 2-YEAR RETURN PERIOD
Rank 3 Eqn 3 $y=a+bx^{1.5}$
$r^2=0.92127346$ DF Adj $r^2=0.91785057$ FitStdErr=0.37105554 Fstat=550.00328
$a=1.2210626$
$b=2.5209434e-05$

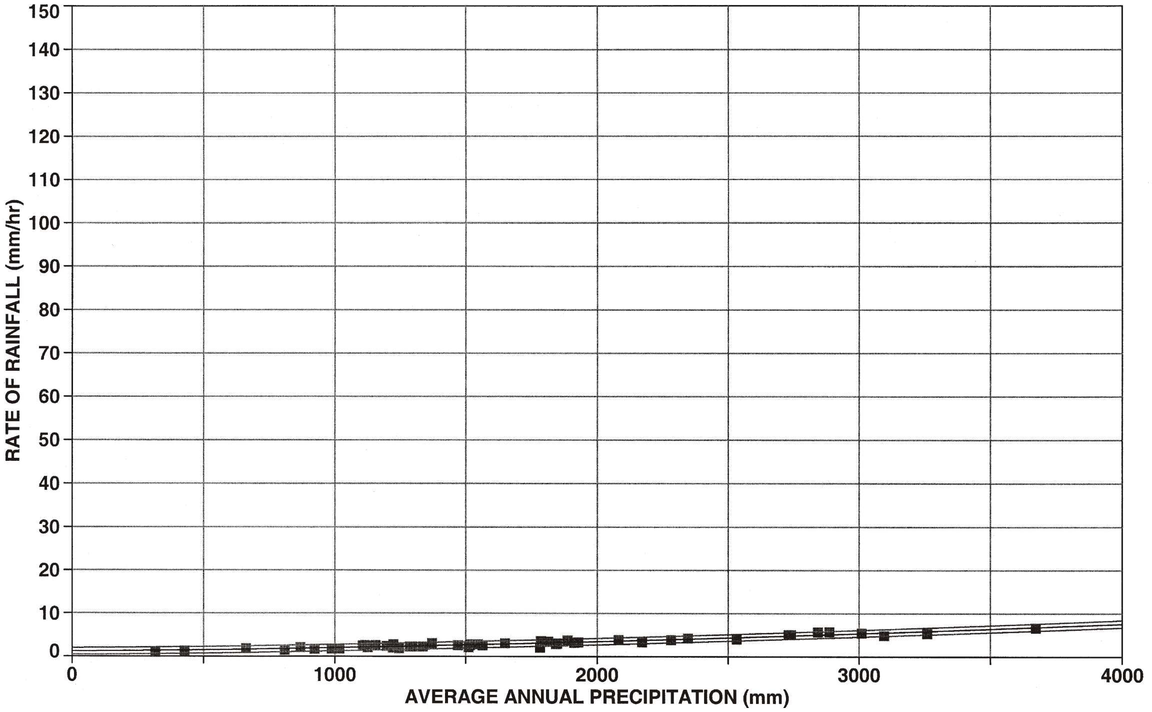


Figure 5.1: Examples of developed relationships between rainfall intensity and average annual precipitation.

TABLE 3.1: LIST OF CLIMATE STATIONS USED IN THIS STUDY SORTED BY AVERAGE ANNUAL PRECIPITATION

STATION NAME	STATION NUMBER	START YEAR	END YEAR	YEARS OF RECORD	ELEVATION	AVERAGE ANNUAL PRECIP.
					(m)	(mm)
Lillooet Seton BCHPA	1114627	1971	1999	20	198	317
Lytton	1114741	1970	1991	19	256	428
Victoria Gonzales Hts	1018610	1900	1999	90	70	661
Victoria Shelbourne	101QF57	1964	1991	10	49	809
Victoria International A	1018620	1940	1999	58	19	869
Nanaimo Departure Bay	1025C70	1913	1992	59	8	922
Ladner	1104470	1952	1971	17	1	988
Merry Island	1045100	1957	1999	35	8	1,017
Campbell River A	1021261	1965	1999	31	106	1,106
Nanaimo A	1025370	1947	1999	47	28	1,115
Vancouver A/ Vancouver International A	1108447	1937	1999	61	4	1,125
Nanaimo City Yard	10253G0	1981	1999	14	114	1,129
Pitt Meadows STP	110FAG9	1974	1993	18	5	1,155
Comox A	1021830	1944	1999	54	24	1,198
Powell River A	1046391	1954	1999	31	130	1,221
Victoria Marine/ Victoria Marine Radio	1018642	1967	1992	23	32	1,223
Powell River Westview	1046410	1960	1986	15	55	1,245
Vancouver UBC	1108487	1957	1995	34	87	1,285
Campbell River STP	1021265	1982	1996	11	3	1,296
Surrey Municipal Hall	1107876	1962	1999	36	76	1,336
Courtenay/Courtenay Puntlege BCHB	1021990	1921	1964	33	24	1,371
Langley Lochiel	1104555	1957	1986	24	101	1,470
Gibsons	1043150	1949	1998	18	62	1,510
Vancouver Harbour/ Vancouver Harbour CS	1108446	1925	1999	49	3	1,516
Vancouver PMO	1108465	1900	1979	75	59	1,517
Abbotsford A	1100030	1944	1999	52	58	1,546
Surrey Kwantlen Pk	1107873	1960	1998	30	93	1,563
Agassiz/Agassiz CDA	1100120	1900	1999	97	15	1,649
White Rock STP	1108914	1964	1999	32	15	1,783
Hope/Hope A	1113540	1934	1995	53	36	1,786
Port Hardy A	1026270	1944	1999	53	22	1,814
Daisy Lake Dam	1042255	1968	1983	12	381	1,843
Mission West Abbey	1105192	1963	1999	33	221	1,848
Port Alberni A	1036206	1969	1996	25	2	1,887
Port Coquitlam City Yard	1106256	1971	1990	16	7	1,912
Port Moody Glenayre (Gulf Oil Rfy)	1106CL2	1970	1999	25	130	1,928
Cowichan Lake Village	1012055	1960	1999	31	171	2,081
Clowhom Falls	1041710	1932	1990	54	23	2,170
Pitt Polder	1106180	1951	1999	45	5	2,281
Squamish	10476F0	1982	1999	12	52	2,346
Alouette Lake	1100360	1924	1982	59	117	2,532
Buntzen Lake	1101140	1924	1983	50	10	2,731
North Vancouver Lynn Creek	1105660	1964	1983	17	191	2,739
Carnation Creek CDF	1031413	1971	1990	15	61	2,843
Port Mellon	1046330	1942	1989	30	8	2,887
Estevan Point	1032730	1908	1999	74	7	3,010
Amphitrite Point	1030426	1980	1999	15	27	3,096
Tofino A	1038205	1942	1999	40	24	3,259
Port Renfrew BCFP	1016335	1970	1999	23	12	3,672

TABLE 4.1: COMPARISON OF CHANGES IN PRECIPITATION PREDICTED BY THE GCMII AND CGCMI MODELS

PREDICTED CHANGE IN AVERAGE PRECIPITATION (%)														
MODEL	PREDICTION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
GCMII	2 x CO_2 equilibrium	60	13	5	13	-30	-25	5	5	-25	5	15	40	13
CGCMI	2020 relative to 1961-1990 mean	7	13	1	-5	-19	-10	-13	-1	17	1	0	9	2 (est)
	2050 relative to 1961-1990 mean	10	9	10	-6	-28	-5	-10	-8	17	8	5	12	5 (est)
	2080 relative to 1961-1990 mean	20	15	10	-7	-31	-18	4	5	21	16	11	18	10 (est)

GCMII – Global Circulation Model II
CGCMI – Coupled Global Circulation Model I
Data Source for GCMII – Eric Taylor, pers. comm.
Data Source for CGCMI – http://www.pyr.ec.gc.ca/climate-change/scenarios_e.htm

TABLE 5.1: CORRELATION COEFFICIENTS FOR BEST FIT RELATIONSHIPS BETWEEN RAINFALL INTENSITY AND AVERAGE ANNUAL PRECIPITATION.

RAINFALL INTENSITY DURATION		r^2 VALUE FOR BEST FIT RELATIONSHIP WITH ANNUAL PRECIPITATION FOR A RETURN PERIOD OF:					
MINUTES	**HOURS**	**2 years**	**5 years**	**10 years**	**25 years**	**50 years**	**100 years**
5		0.53	0.41	0.33	0.26	0.23	0.20
10		0.56	0.36	0.26	0.18	0.13	0.10
15		0.59	0.40	0.30	0.21	0.17	0.13
30		0.69	0.53	0.42	0.32	0.26	0.22
	1	0.81	0.68	0.61	0.53	0.46	0.44
	2	0.90	0.84	0.79	0.72	0.69	0.65
	6	0.91	0.90	0.88	0.86	0.84	0.83
	12	0.91	0.89	0.86	0.85	0.84	0.83
	24	0.92	0.88	0.87	0.84	0.82	0.81

NOTE 1: Tabulated r^2 values have been adjusted for the number of degrees of freedom.

An r^2 value of 0.91 indicates that 91% of the variation in rainfall intensity is predicted by the developed relationship with average annual precipitation.

TABLE 5.2: BEST-FIT EQUATIONS TO ESTIMATE 5 to 30 MINUTE RAINFALL INTENSITIES ON THE BASIS OF AVERAGE ANNUAL PRECIPITATION

RAINFALL–INTENSITY–DURATION (y)	RETURN PERIOD (years)	BEST-FIT RELATIONSHIP BASED ON AVERAGE ANNUAL PRECIPITATION (x)	COEFFICIENT OF DETERMINATION (Adj r²)
5 MINUTES	2	$y = 8.449106 + 0.71435106\,x^{0.5}$	0.53
	5	$y = 15.871575 + 0.8844559\,x^{0.5}$	0.41
	10	$y = 20.892958 + 0.99504217\,x^{0.5}$	0.33
	25	$y = 27.117507 + 1.1369083\,x^{0.5}$	0.26
	50	$y = 31.752503 + 1.2419142\,x^{0.5}$	0.23
	100	$y = 36.378437 + 1.3458193\,x^{0.5}$	0.20
10 MINUTES	2	$y = 6.1485324 + 0.52325801\,x^{0.5}$	0.56
	5	$y = 13.752569 + 0.57702101\,x^{0.5}$	0.36
	10	$y = 18.808156 + 0.61237222\,x^{0.5}$	0.26
	25	$y = 25.133452 + 0.65807563\,x^{0.5}$	0.18
	50	$y = 29.926877 + 0.68982127\,x^{0.5}$	0.13
	100	$y = 34.617448 + 0.72289287\,x^{0.5}$	0.10
15 MINUTES	2	$y = 4.3691851 + 0.45323285\,x^{0.5}$	0.59
	5	$y = 10.328153 + 0.49654199\,x^{0.5}$	0.40
	10	$y = 14.216995 + 0.52714824\,x^{0.5}$	0.30
	25	$y = 19.161947 + 0.56438958\,x^{0.5}$	0.21
	50	$y = 22.856582 + 0.59138251\,x^{0.5}$	0.17
	100	$y = 26.462619 + 0.6197127\,x^{0.5}$	0.13
30 MINUTES	2	$y = 2.0258487 + 0.34961679\,x^{0.5}$	0.69
	5	$y = 5.2114117 + 0.39764516\,x^{0.5}$	0.53
	10	$y = 7.3562166 + 0.42891346\,x^{0.5}$	0.42
	25	$y = 9.9948978 + 0.46985385\,x^{0.5}$	0.32
	50	$y = 11.985402 + 0.4993854\,x^{0.5}$	0.26
	100	$y = 13.949746 + 0.52927808\,x^{0.5}$	0.22

TABLE 5.3: BEST-FIT EQUATIONS TO ESTIMATE 1 TO 24-HOUR RAINFALL INTENSITIES ON THE BASIS OF AVERAGE ANNUAL PRECIPITATION

RAINFALL–INTENSITY–DURATION (y)	RETURN PERIOD (years)	BEST-FIT RELATIONSHIP BASED ON AVERAGE ANNUAL PRECIPITATION (x)	COEFFICIENT OF DETERMINATION (Adj r²)
1	2	$y = 5.178127 + 0.0037149161\,x$	0.81
	5	$y = 7.3340882 + 0.0044430088\,x$	0.68
	10	$y = 12.831424 + 1.2466231e-06\,x^{2}$	0.61
	25	$y = 16.683895 + 4.0735758e-10\,x^{3}$	0.53
	50	$y = 18.530978 + 4.1292714e-10\,x^{3}$	0.46
	100	$y = 20.327482 + 4.7609552e-10\,x^{3}$	0.44
2	2	$lny = 1.5537818 + 0.00035030783\,x$	0.90
	5	$y = 7.5141002 + 1.0078624e-06\,x^{2}$	0.84
	10	$y = 8.6221468 + 1.1117023e-06\,x^{2}$	0.79
	25	$y = 10.845402 + 2.1071279e-08\,x^{2.5}$	0.72
	50	$y = 11.928555 + 2.2794304e-08\,x^{2.5}$	0.69
	100	$y = 13.665412 + 4.182931e-10\,x^{3}$	0.65
6	2	$lny = 1.0630308 + 0.00040518851\,x$	0.91
	5	$y = 4.4007771 + 8.2607028e-07\,x^{2}$	0.90
	10	$y = 5.5486479 + 1.56302e-08\,x^{2.5}$	0.88
	25	$y = 6.2947887 + 1.7741262e-08\,x^{2.5}$	0.86
	50	$y = 6.8542188 + 1.9210352e-08\,x^{2.5}$	0.84
	100	$y = 7.3924515 + 2.0821349e-08\,x^{2.5}$	0.83
12	2	$y = 1.972927 + 3.2395563e-05\,x^{1.5}$	0.91
	5	$y = 2.4605292 + 3.9567747e-05\,x^{1.5}$	0.89
	10	$y = 2.6620246 + 4.5245715e-05\,x^{1.5}$	0.86
	25	$y = 4.1079898 + 8.2931247e-07\,x^{2}$	0.85
	50	$y = 4.4946957 + 9.0340871e-07\,x^{2}$	0.84
	100	$y = 4.8725986 + 9.7780952e-07\,x^{2}$	0.83
24	2	$y = 1.2210626 + 2.5209434e-05\,x^{1.5}$	0.92
	5	$y = 1.569024 + 3.1575291e-05\,x^{1.5}$	0.88
	10	$y = 1.7774162 + 3.6097872e-05\,x^{1.5}$	0.87
	25	$y = 12.0861471 + 4.1242976e-05\,x^{1.5}$	0.84
	50	$y = 2.3058954 + 4.5123082e-05\,x^{1.5}$	0.82
	100	$y = 2.5064207 + 4.9260065e-05\,x^{1.5}$	0.81

TABLE 7.1: COMPARISON OF 2-YEAR RETURN PERIOD RAINFALL INTENSITIES WITH CAINE'S CRITERIA FOR SLOPE INSTABILITY

[Note - shaded cells indicate that Caine's criterion is exceeded]

STATION	YEARS OF RECORD	AVERAGE ANNUAL PRECIPITATION (mm)	2-YEAR RETURN PERIOD RAINFALL (mm) COMPARED WITH CAINE'S CRITERION FOR SLOPE FAILURE INITIATION FOR A DURATION OF:																	
			5 min		10 min		15 min		30 min		1 hour		2 hour		6 hour		12 hour		24 hour	
			Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion
Lilooet Seton BCHPA	20	317									5.8	14.8	8.6	22.6	15.8	44.2	20.2	67.4	23.0	102.96
Lytton	19	428	1.5	3.3	2.2	5.0	2.8	6.4	4.2	9.7	6.7	14.8	10.5	22.6	20.6	44.2	26.1	67.4	31.3	102.96
Victoria Gonzales Hts	90	661	1.9	3.3	2.6	5.0	3.2	6.4	4.7	9.7	7.5	14.8	11.7	22.6	24.3	44.2	34.5	67.4	44.4	102.96
Victoria Shelbourne	10	809	1.7	3.3	2.5	5.0	3.1	6.4	4.7	9.7	6.9	14.8	10.2	22.6	21.1	44.2	29.0	67.4	36.8	102.96
Victoria Int'l A	58	869	2.7	3.3	3.8	5.0	4.6	6.4	6.2	9.7	8.8	14.8	13.5	22.6	28.0	44.2	39.6	67.4	49.4	102.96
Nanaimo Departure Bay	59	922									8.5	14.8	12.7	22.6	22.8	44.2	31.8	67.4	41.9	102.96
Ladner	17	988	2.0	3.3	3.3	5.0	4.0	6.4	5.6	9.7	7.7	14.8	11.5	22.6	21.0	44.2	28.5	67.4	42.8	102.96
Merry Island	35	1,017									10.6	14.8	15.0	22.6	24.2	44.2	31.1	67.4	42.5	102.96
Campbell River A	31	1,106	3.4	3.3	4.9	5.0	6.0	6.4	8.2	9.7	11.0	14.8	16.4	22.6	32.9	44.2	45.6	67.4	60.8	102.96
Nanaimo A	47	1,115	2.3	3.3	3.4	5.0	4.4	6.4	6.5	9.7	10.0	14.8	15.0	22.6	30.9	44.2	44.8	67.4	62.3	102.96
Vancouver Int'l A	61	1,125	2.9	3.3	4.4	5.0	5.5	6.4	7.2	9.7	9.7	14.8	13.4	22.6	25.1	44.2	37.1	67.4	49.6	102.96
Nanaimo City Yard	14	1,129	3.1	3.3	4.7	5.0	5.8	6.4	7.5	9.7	10.3	14.8	15.0	22.6	29.5	44.2	44.4	67.4	59.1	102.96
Pitt Meadows STP	18	1,155	3.7	3.3	5.3	5.0	6.5	6.4	9.3	9.7	10.9	14.8	15.9	22.6	31.1	44.2	44.5	67.4	63.3	102.96
Comox A	54	1,198	2.8	3.3	4.1	5.0	5.1	6.4	7.0	9.7	9.7	14.8	14.6	22.6	29.3	44.2	42.7	67.4	57.3	102.96
Powell River A	31	1,221	3.7	3.3	5.2	5.0	6.3	6.4	8.7	9.7	11.9	14.8	16.0	22.6	27.7	44.2	35.7	67.4	48.5	102.96
Victoria Marine/Vic Marine Radio	23	1,223	2.2	3.3	3.2	5.0	4.1	6.4	6.2	9.7	9.0	14.8	15.9	22.6	34.1	44.2	50.2	67.4	67.6	102.96
Powell River Westview	15	1,245									10.4	14.8	14.2	22.6	23.1	44.2	32.8	67.4	44.4	102.96
Vancouver UBC	34	1,285	3.0	3.3	4.5	5.0	5.4	6.4	7.1	9.7	9.5	14.8	13.3	22.6	26.4	44.2	40.2	67.4	54.7	102.96
Campbell River STP	11	1,296	3.6	3.3	4.9	5.0	6.1	6.4	8.6	9.7	11.9	14.8	17.8	22.6	32.0	44.2	43.6	67.4	55.3	102.96
Surrey Municipal Hall	36	1,336	2.9	3.3	4.1	5.0	5.3	6.4	7.1	9.7	10.2	14.8	14.4	22.6	26.5	44.2	38.8	67.4	54.5	102.96
Courtenay Puntledge BCHP	33	1,371									10.7	14.8	16.4	22.6	36.1	44.2	53.8	67.4	73.6	102.96
Langley Lochiel	24	1,470									10.4	14.8	15.7	22.6	30.1	44.2	45.1	67.4	63.0	102.96
Gibsons	18	1,510									9.8	14.8	14.0	22.6	24.6	44.2	35.1	67.4	50.4	102.96
Vancouver Harbour CS	49	1,516	3.4	3.3	5.3	5.0	6.5	6.4	8.8	9.7	11.3	14.8	16.3	22.6	30.7	44.2	45.6	67.4	62.1	102.96
Vancouver PMO	75	1,517									9.6	14.8	15.3	22.6	32.3	44.2	49.6	67.4	68.1	102.96
Abbotsford A	52	1,546	3.6	3.3	5.3	5.0	6.7	6.4	9.6	9.7	13.3	14.8	18.2	22.6	33.9	44.2	49.8	67.4	67.8	102.96
Surrey Kwantlen Park	30	1,563	3.1	3.3	4.5	5.0	5.4	6.4	7.6	9.7	10.7	14.8	16.0	22.6	31.4	44.2	45.7	67.4	63.2	102.96
Agassiz CDA	97	1,649	2.3	3.3	3.7	5.0	4.6	6.4	6.7	9.7	10.3	14.8	15.8	22.6	32.2	44.2	49.6	67.4	73.9	102.96
White Rock STP	32	1,783	2.9	3.3	4.3	5.0	5.3	6.4	7.7	9.7	11.4	14.8	15.8	22.6	28.1	44.2	37.8	67.4	50.2	102.96
Hope Airport	53	1,786	3.0	3.3	4.5	5.0	5.7	6.4	8.6	9.7	13.3	14.8	20.7	22.6	41.8	44.2	62.9	67.4	86.7	102.96
Port Hardy A	53	1,814	3.2	3.3	4.4	5.0	5.4	6.4	7.4	9.7	11.0	14.8	17.3	22.6	37.8	44.2	60.3	67.4	83.3	102.96
Daisy Lake Dam	12	1,843									10.1	14.8	15.3	22.6	31.6	44.2	46.4	67.4	68.6	102.96
Mission West Abbey	33	1,848	3.5	3.3	5.4	5.0	6.8	6.4	9.6	9.7	13.7	14.8	19.9	22.6	35.7	44.2	52.4	67.4	74.0	102.96
Port Alberni A	25	1,887	2.7	3.3	4.0	5.0	5.1	6.4	7.5	9.7	10.8	14.8	17.9	22.6	40.4	44.2	62.8	67.4	91.1	102.96
Port Coquitlam City Yard	16	1,912	2.9	3.3	4.4	5.0	5.6	6.4	7.5	9.7	11.9	14.8	16.8	22.6	34.8	44.2	54.2	67.4	76.0	102.96
Port Moody Glenayre	25	1,928									11.1	14.8	17.4	22.6	37.3	44.2	56.9	67.4	78.8	102.96
Cowichan Lake Village	31	2,081									11.0	14.8	17.2	22.6	38.6	44.2	60.9	67.4	94.1	102.96
Clowhom Falls	54	2,170									10.2	14.8	16.4	22.6	34.4	44.2	53.5	67.4	81.7	102.96
Pitt Polder	45	2,281	3.8	3.3	5.3	5.0	6.7	6.4	9.2	9.7	12.7	14.8	19.4	22.6	40.6	44.2	63.2	67.4	93.5	102.96
Squamish	12	2,346	2.8	3.3	4.1	5.0	4.9	6.4	7.3	9.7	11.6	14.8	19.4	22.6	42.8	44.2	67.7	67.4	103.8	102.96
Alouette Lake	59	2,532									12.4	14.8	20.3	22.6	43.8	44.2	68.8	67.4	96.8	102.96
Buntzen Lake	50	2,731									15.6	14.8	24.2	22.6	53.8	44.2	81.9	67.4	123.5	102.96
N Vancouver Lynn Creek	17	2,739	4.0	3.3	5.6	5.0	7.0	6.4	10.3	9.7	14.5	14.8	23.4	22.6	51.5	44.2	80.2	67.4	122.3	102.96
Carnation Creek CDF	15	2,843	3.8	3.3	5.1	5.0	6.4	6.4	10.0	9.7	15.4	14.8	25.1	22.6	56.2	44.2	87.2	67.4	136.7	102.96
Port Mellon	30	2,887	3.4	3.3	5.4	5.0	7.2	6.4	11.0	9.7	17.6	14.8	28.6	22.6	64.0	44.2	99.3	67.4	138.1	102.96
Estevan Point	74	3,010	3.9	3.3	6.1	5.0	7.6	6.4	11.2	9.7	18.0	14.8	28.0	22.6	59.7	44.2	86.7	67.4	132.0	102.96
Amphitrite Point	15	3,096	4.5	3.3	6.2	5.0	7.5	6.4	10.5	9.7	16.6	14.8	29.2	22.6	61.9	44.2	86.4	67.4	118.7	102.96
Tofino A	40	3,259	4.3	3.3	6.4	5.0	8.3	6.4	11.8	9.7	17.3	14.8	28.4	22.6	58.9	44.2	86.3	67.4	129.6	102.96
Port Renfrew	23	3,672									22.3	14.8	35.9	22.6	77.8	44.2	113.8	67.4	160.4	102.96
Number of Values with Rainfall ≤ 2-years Return Period Criterion			**14**		**12**		**11**		**6**		**7**		**8**		**8**		**10**		**9**	
Number of Stations			**34**		**34**		**34**		**34**		**49**		**49**		**49**		**49**		**49**	
Percentage of Values with Rainfall≤ 2-years Return Period Criterion			**41**		**35**		**32**		**18**		**14**		**16**		**16**		**20**		**18**	

TABLE 7.2: COMPARISON OF 2-YEAR RETURN PERIOD RAINFALL INTENSITIES WITH INNES' CRITERIA FOR SLOPE INSTABILITY [Note - shaded cells indicate that Innes' criterion is exceeded]

STATION	YEARS OF RECORD	AVERAGE ANNUAL PRECIPITATION (mm)	2-YEAR RETURN PERIOD RAINFALL (mm) COMPARED WITH INNES'S CRITERION FOR SLOPE FAILURE INITIATION FOR A DURATION OF:																	
			5 min		10 min		15 min		30 min		1 hour		2 hour		6 hour		12 hour		24 hour	
			Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion	Rainfall	Initiation Criterion
Lilooet Seton BCHPA	20	317									5.8	4.9	8.6	7.0	15.8	12.2	20.2	17.3	23.0	24.48
Lytton	19	428	1.5	1.4	2.2	2.0	2.8	2.5	4.2	3.5	6.7	4.9	10.5	7.0	20.6	12.2	26.1	17.3	31.3	24.48
Victoria Gonzales Hts	90	661	1.9	1.4	2.6	2.0	3.2	2.5	4.7	3.5	7.5	4.9	11.7	7.0	24.3	12.2	34.5	17.3	44.4	24.48
Victoria Shelbourne	10	809	1.7	1.4	2.5	2.0	3.1	2.5	4.7	3.5	6.9	4.9	10.2	7.0	21.1	12.2	29.0	17.3	36.8	24.48
Victoria Int'l A	58	869	2.7	1.4	3.8	2.0	4.6	2.5	6.2	3.5	8.8	4.9	13.5	7.0	28.0	12.2	39.6	17.3	49.4	24.48
Nanaimo Departure Bay	59	922									8.5	4.9	12.7	7.0	22.8	12.2	31.8	17.3	41.9	24.48
Ladner	17	988	2.0	1.4	3.3	2.0	4.0	2.5	5.6	3.5	7.7	4.9	11.5	7.0	21.0	12.2	28.5	17.3	42.8	24.48
Merry Island	35	1,017									10.6	4.9	15.0	7.0	24.2	12.2	31.1	17.3	42.5	24.48
Campbell River A	31	1,106	3.4	1.4	4.9	2.0	6.0	2.5	8.2	3.5	11.0	4.9	16.4	7.0	32.9	12.2	45.6	17.3	60.8	24.48
Nanaimo A	47	1,115	2.3	1.4	3.4	2.0	4.4	2.5	6.5	3.5	10.0	4.9	15.0	7.0	30.9	12.2	44.8	17.3	62.3	24.48
Vancouver Int'l A	61	1,125	2.9	1.4	4.4	2.0	5.5	2.5	7.2	3.5	9.7	4.9	13.4	7.0	25.1	12.2	37.1	17.3	49.6	24.48
Nanaimo City Yard	14	1,129	3.1	1.4	4.7	2.0	5.8	2.5	7.5	3.5	10.3	4.9	15.0	7.0	29.5	12.2	44.4	17.3	59.1	24.48
Pitt Meadows STP	18	1,155	3.7	1.4	5.3	2.0	6.5	2.5	9.3	3.5	10.9	4.9	15.9	7.0	31.1	12.2	44.5	17.3	63.3	24.48
Comox A	54	1,198	2.8	1.4	4.1	2.0	5.1	2.5	7.0	3.5	9.7	4.9	14.6	7.0	29.3	12.2	42.7	17.3	57.3	24.48
Powell River A	31	1,221	3.7	1.4	5.2	2.0	6.3	2.5	8.7	3.5	11.9	4.9	16.0	7.0	27.7	12.2	35.7	17.3	48.5	24.48
Victoria Marine/Vic Marine Radio	23	1,223	2.2	1.4	3.2	2.0	4.1	2.5	6.2	3.5	9.0	4.9	15.9	7.0	34.1	12.2	50.2	17.3	67.6	24.48
Powell River Westview	15	1,245									10.4	4.9	14.2	7.0	23.1	12.2	32.8	17.3	44.4	24.48
Vancouver UBC	34	1,285	3.0	1.4	4.5	2.0	5.4	2.5	7.1	3.5	9.5	4.9	13.3	7.0	26.4	12.2	40.2	17.3	54.7	24.48
Campbell River STP	11	1,296	3.6	1.4	4.9	2.0	6.1	2.5	8.6	3.5	11.9	4.9	17.8	7.0	32.0	12.2	43.6	17.3	55.3	24.48
Surrey Municipal Hall	36	1,336	2.9	1.4	4.1	2.0	5.3	2.5	7.1	3.5	10.2	4.9	14.4	7.0	26.5	12.2	38.8	17.3	54.5	24.48
Courtenay Puntledge BCHP	33	1,371									10.7	4.9	16.4	7.0	36.1	12.2	53.8	17.3	73.6	24.48
Langley Lochiel	24	1,470									10.4	4.9	15.7	7.0	30.1	12.2	45.1	17.3	63.0	24.48
Gibsons	18	1,510									9.8	4.9	14.0	7.0	24.6	12.2	35.1	17.3	50.4	24.48
Vancouver Harbour CS	49	1,516	3.4	1.4	5.3	2.0	6.5	2.5	8.8	3.5	11.3	4.9	16.3	7.0	30.7	12.2	45.6	17.3	62.1	24.48
Vancouver PMO	75	1,517									9.6	4.9	15.3	7.0	32.3	12.2	49.6	17.3	68.1	24.48
Abbotsford A	52	1,546	3.6	1.4	5.3	2.0	6.7	2.5	9.6	3.5	13.3	4.9	18.2	7.0	33.9	12.2	49.8	17.3	67.8	24.48
Surrey Kwantlen Park	30	1,563	3.1	1.4	4.5	2.0	5.4	2.5	7.6	3.5	10.7	4.9	16.0	7.0	31.4	12.2	45.7	17.3	63.2	24.48
Agassiz CDA	97	1,649	2.3	1.4	3.7	2.0	4.6	2.5	6.7	3.5	10.3	4.9	15.8	7.0	32.2	12.2	49.6	17.3	73.9	24.48
White Rock STP	32	1,783	2.9	1.4	4.3	2.0	5.3	2.5	7.7	3.5	11.4	4.9	15.8	7.0	28.1	12.2	37.8	17.3	50.2	24.48
Hope Airport	53	1,786	3.0	1.4	4.5	2.0	5.7	2.5	8.6	3.5	13.3	4.9	20.7	7.0	41.8	12.2	62.9	17.3	86.7	24.48
Port Hardy A	53	1,814	3.2	1.4	4.4	2.0	5.4	2.5	7.4	3.5	11.0	4.9	17.3	7.0	37.8	12.2	60.3	17.3	83.3	24.48
Daisy Lake Dam	12	1,843									10.1	4.9	15.3	7.0	31.6	12.2	46.4	17.3	68.6	24.48
Mission West Abbey	33	1,848	3.5	1.4	5.4	2.0	6.8	2.5	9.6	3.5	13.7	4.9	19.9	7.0	35.7	12.2	52.4	17.3	74.0	24.48
Port Alberni A	25	1,887	2.7	1.4	4.0	2.0	5.1	2.5	7.5	3.5	10.8	4.9	17.9	7.0	40.4	12.2	62.8	17.3	91.1	24.48
Port Coquitlam City Yard	16	1,912	2.9	1.4	4.4	2.0	5.6	2.5	7.5	3.5	11.9	4.9	16.8	7.0	34.8	12.2	54.2	17.3	76.0	24.48
Port Moody Glenayre	25	1,928									11.1	4.9	17.4	7.0	37.3	12.2	56.9	17.3	78.8	24.48
Cowichan Lake Village	31	2,081									11.0	4.9	17.2	7.0	38.6	12.2	60.9	17.3	94.1	24.48
Clowhom Falls	54	2,170									10.2	4.9	16.4	7.0	34.4	12.2	53.5	17.3	81.7	24.48
Pitt Polder	45	2,281	3.8	1.4	5.3	2.0	6.7	2.5	9.2	3.5	12.7	4.9	19.4	7.0	40.6	12.2	63.2	17.3	93.5	24.48
Squamish	12	2,346	2.8	1.4	4.1	2.0	4.9	2.5	7.3	3.5	11.6	4.9	19.4	7.0	42.8	12.2	67.7	17.3	103.8	24.48
Alouette Lake	59	2,532									12.4	4.9	20.3	7.0	43.8	12.2	68.8	17.3	96.8	24.48
Buntzen Lake	50	2,731									15.6	4.9	24.2	7.0	53.8	12.2	81.9	17.3	123.5	24.48
N Vancouver Lynn Creek	17	2,739	4.0	1.4	5.6	2.0	7.0	2.5	10.3	3.5	14.5	4.9	23.4	7.0	51.5	12.2	80.2	17.3	122.3	24.48
Carnation Creek CDF	15	2,843	3.8	1.4	5.1	2.0	6.4	2.5	10.0	3.5	15.4	4.9	25.1	7.0	56.2	12.2	87.2	17.3	136.7	24.48
Port Mellon	30	2,887	3.4	1.4	5.4	2.0	7.2	2.5	11.0	3.5	17.6	4.9	28.6	7.0	64.0	12.2	99.3	17.3	138.1	24.48
Estevan Point	74	3,010	3.9	1.4	6.1	2.0	7.6	2.5	11.2	3.5	18.0	4.9	28.0	7.0	59.7	12.2	86.7	17.3	132.0	24.48
Amphitrite Point	15	3,096	4.5	1.4	6.2	2.0	7.5	2.5	10.5	3.5	16.6	4.9	29.2	7.0	61.9	12.2	86.4	17.3	118.7	24.48
Tofino A	40	3,259	4.3	1.4	6.4	2.0	8.3	2.5	11.8	3.5	17.3	4.9	28.4	7.0	58.9	12.2	86.3	17.3	129.6	24.48
Port Renfrew	23	3,672									22.3	4.9	35.9	7.0	77.8	12.2	113.8	17.3	160.4	24.48
Number of Values with Rainfall # 2-years Return Period Criterion			**34**		**34**		**34**		**34**		**49**		**49**		**49**		**49**		**49**	
Number of Stations			**34**		**34**		**34**		**34**		**49**		**49**		**49**		**49**		**49**	
Percentage of Values with Rainfall# 2-years Return Period Criterion			**100**		**100**		**100**		**100**		**100**		**100**		**100**		**100**		**100**	

TABLE 8.2.1: PREDICTED FREQUENCY OF EXCEEDING CAINE'S INSTABILITY CRITERION BASED ON THE PRESENT PRECIPITATION REGIME.

RAINFALL DURATION	**AVERAGE RETURN PERIOD (years) FOR EXCEEDING CAINE'S SLOPE INITIATION CRITERIA FOR SITES HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:**				
	300 - 1000 mm	**1,000 TO 1,500 mm**	**1,500 TO 2,000 mm**	**2,000 TO 3,000 mm**	**3,000 TO 3,700 mm**
5 minutes	5.7	2.9	2.1	1.4	1.0
10 minutes	6.1	3.3	2.3	1.6	1.2
15 minutes	7.7	3.9	2.5	1.5	1.0
30 minutes	14.9	5.7	3.4	2.0	1.3
1 hour	13.2	10.2	6.5	2.4	0.9
2 hours	29.6	18.4	7.6	1.9	0.6
6 hours	66.5	30.7	9.5	1.6	0.3
12 hours	160.6	38.9	9.2	1.6	0.4
24 hours.	2207.1	67.1	10.4	1.7	0.5

TABLE 8.2.2: PREDICTED FREQUENCY OF EXCEEDING CAINE'S INSTABILITY CRITERION BASED ON A 5% INCREASE IN ANNUAL PRECIPITATION.

RAINFALL DURATION	AVERAGE RETURN PERIOD (years) FOR EXCEEDING CAINE'S SLOPE INITIATION CRITERIA FOR SITES HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	5.5	2.8	2.0	1.3	1.0
10 minutes	5.8	3.2	2.2	1.5	1.1
15 minutes	7.4	3.6	2.3	1.4	0.9
30 minutes	14.0	5.3	3.2	1.8	1.2
1 hour	13.0	9.8	5.9	2.1	0.7
2 hours	28.8	16.8	6.5	1.6	0.5
6 hours	63.8	27.1	7.7	1.2	0.2
12 hours	150.7	32.6	7.4	1.2	0.3
24 hours.	1950.9	51.9	8.0	1.4	0.4

TABLE 8.2.3: PREDICTED FREQUENCY OF EXCEEDING CAINE'S INSTABILITY CRITERION BASED ON A 10% INCREASE IN ANNUAL PRECIPITATION.

RAINFALL DURATION	AVERAGE RETURN PERIOD (years) FOR EXCEEDING CAINE'S SLOPE INITIATION CRITERIA FOR SITES HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	5.2	2.7	1.9	1.3	0.9
10 minutes	5.6	3.0	2.1	1.4	1.1
15 minutes	7.0	3.4	2.2	1.3	0.9
30 minutes	13.1	4.9	3.0	1.7	1.1
1 hour	12.8	9.3	5.3	1.7	0.6
2 hours	28.1	15.3	5.5	1.3	0.4
6 hours	61.2	23.8	6.2	0.9	0.2
12 hours	141.4	27.3	5.9	0.9	0.2
24 hours.	1727.5	40.6	6.3	1.1	0.4

TABLE 8.2.4: PREDICTED FREQUENCY OF EXCEEDING CAINE'S INSTABILITY CRITERION BASED ON A 20% INCREASE IN ANNUAL PRECIPITATION.

RAINFALL DURATION	AVERAGE RETURN PERIOD (years) FOR EXCEEDING CAINE'S SLOPE INITIATION CRITERIA FOR SITES HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	4.8	2.5	1.7	1.1	0.8
10 minutes	5.2	2.8	1.9	1.3	1.0
15 minutes	6.5	3.1	1.9	1.1	0.8
30 minutes	11.7	4.3	2.6	1.5	1.0
1 hour	12.4	8.4	4.3	1.3	0.4
2 hours	26.4	12.5	4.0	0.9	0.3
6 hours	56.0	18.2	4.1	0.6	0.1
12 hours	124.7	19.3	3.9	0.6	0.1
24 hours.	1360.9	25.5	4.1	0.8	0.3

TABLE 8.2.5: PREDICTED FREQUENCY OF EXCEEDING CAINE'S INSTABILITY CRITERION BASED ON A 30% INCREASE IN ANNUAL PRECIPITATION.

RAINFALL DURATION	AVERAGE RETURN PERIOD (years) FOR EXCEEDING CAINE'S SLOPE INITIATION CRITERIA FOR SITES HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	4.4	2.3	1.6	1.0	0.8
10 minutes	4.8	2.6	1.8	1.2	0.9
15 minutes	6.0	2.8	1.7	1.0	0.7
30 minutes	10.5	3.9	2.3	1.3	0.9
1 hour	12.0	7.5	3.4	0.9	0.3
2 hours	24.7	10.0	2.9	0.6	0.2
6 hours	51.1	13.7	2.7	0.4	0.1
12 hours	110.3	13.8	2.6	0.4	0.1
24 hours.	1077.8	16.6	2.7	0.6	0.2

TABLE 8.2.6: INCREASE IN THE FREQUENCY OF EXCEEDING CAINE'S SLOPE INSTABILITY CRITERION DUE TO A 5% INCREASE IN AVERAGE ANNUAL PRECIPITATION

RAINFALL DURATION	INCREASED FREQUENCY OF EXCEEDING CAINE'S CRITERIA (%) FOR SITES PRESENTLY HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	105	105	105	105	106
10 minutes	104	105	105	105	105
15 minutes	105	106	107	107	107
30 minutes	107	107	107	107	108
1 hour	101	105	110	118	123
2 hours	103	109	118	123	124
6 hours	104	113	124	131	132
12 hours	107	119	125	129	128
24 hours.	113	129	129	125	119

TABLE 8.2.7: INCREASE IN THE FREQUENCY OF EXCEEDING CAINE'S SLOPE INSTABILITY CRITERION DUE TO A 10% INCREASE IN AVERAGE ANNUAL PRECIPITATION

RAINFALL DURATION	INCREASED FREQUENCY OF EXCEEDING CAINE'S CRITERIA (%) FOR SITES PRESENTLY HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	**1,000 TO 1,500 mm**	**1,500 TO 2,000 mm**	**2,000 TO 3,000 mm**	**3,000 TO 3,700 mm**
5 minutes	110	110	110	111	111
10 minutes	108	110	110	111	111
15 minutes	109	113	114	114	115
30 minutes	113	115	115	115	115
1 hour	103	110	122	140	150
2 hours	105	120	139	149	152
6 hours	109	129	153	170	173
12 hours	114	142	156	164	161
24 hours.	128	165	165	153	139

TABLE 8.2.8: INCREASE IN THE FREQUENCY OF EXCEEDING CAINE'S SLOPE INSTABILITY CRITERION DUE TO A 20% INCREASE IN AVERAGE ANNUAL PRECIPITATION

RAINFALL DURATION	INCREASED FREQUENCY OF EXCEEDING CAINE'S CRITERIA (%) FOR SITES PRESENTLY HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	1,000 TO 1,500 mm	1,500 TO 2,000 mm	2,000 TO 3,000 mm	3,000 TO 3,700 mm
5 minutes	120	120	121	122	123
10 minutes	117	120	121	121	122
15 minutes	119	126	128	129	130
30 minutes	127	130	131	131	131
1 hour	107	121	150	194	219
2 hours	112	147	191	217	222
6 hours	119	169	234	278	284
12 hours	129	201	238	258	243
24 hours.	162	263	256	220	184

TABLE 8.2.9: INCREASE IN THE FREQUENCY OF EXCEEDING CAINE'S SLOPE INSTABILITY CRITERION DUE TO A 30% INCREASE IN AVERAGE ANNUAL PRECIPITATION

RAINFALL DURATION	INCREASED FREQUENCY OF EXCEEDING CAINE'S CRITERIA (%) FOR SITES PRESENTLY HAVING AVERAGE ANNUAL PRECIPITATION TOTALS IN THE RANGE OF:				
	300 - 1000 mm	**1,000 TO 1,500 mm**	**1,500 TO 2,000 mm**	**2,000 TO 3,000 mm**	**3,000 TO 3,700 mm**
5 minutes	129	131	132	133	135
10 minutes	125	130	131	132	133
15 minutes	128	140	143	145	146
30 minutes	141	146	147	148	148
1 hour	111	136	188	268	312
2 hours	119	183	262	307	314
6 hours	130	224	354	439	448
12 hours	146	283	355	391	343
24 hours.	205	403	381	299	232