GVRD Historical and Future Rainfall Analysis Update

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1 August 2007

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Preface

The management of municipal water supply and sewerage services is a responsibility of government. Many of the rules for stormwater management are empirical and well-established. These rules protect domestic and commercial infrastructure against flooding and extreme precipitation events.

Within the context of global climate (temperature) change, what are the regional effects on precipitation? Are the design rules still valid? Even if the mean annual precipitation is unchanged, is the *distribution* of rainfall events; namely, the intensity and frequency increasing?

These questions were answered affirmatively in an earlier report by Kerr Wood Liedal, Associates (2002). After 5 years, the Greater Vancouver Regional District (GVRD) has commissioned the Pacific Climate Impacts Consortium (PCIC) to update the analysis and focus on rainfall intensity and frequency of occurrence of large rainfall events in the Vancouver region. The audience for this report is stormwater engineers, managers, and planners for the GVRD and its members.

This report and update was prepared by Pacific Climate Impacts Consortium (PCIC) staff with additional support from members of the consortium and with assistance of several reviewers identified in the *Acknowledgements*. PCIC is a multi-disciplinary consortium that includes researchers and collaborators who address climate variability and change, and extreme weather events and their impacts, especially on hydrology and water resources.

This report affirms, but qualifies the patterns and trends found in the 2002 report. It also identifies several steps that could be taken to improve the ability to undertake stormwater management and other regional planning in the context of global climate change.

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1 August 2007

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Executive Summary

The final report of a 2002 study (KWL-02) on rainfall extremes prepared by Kerr Wood Liedal Associates Ltd. and published by the Greater Vancouver Regional District (GVRD) recommended conducting updates to the report every five years. Since the time of the original report, the following have become available:

- additional GVRD historical rainfall data (mainly 2002-2005 observations)
- additional data and analysis of the state of the Pacific Decadal Oscillation (PDO)
- regionally-averaged future climate model projections

Furthermore, recent extreme weather events of the last five years provide added motivation to improve understanding of extreme rainfall in the GVRD.

Making use of the new information, Pacific Climate Impacts Consortium staff repeated selected analysis from the original report. In some cases, slight modifications to the methodology were made although the scope of the work remained an update to the original report. In addition to presenting the results of the updated analysis, this report also includes a large amount of technical information regarding the analysis performed to facilitate comparison of methods for future updates. However, this document neither replaces the original report nor can it serve as a complete analysis of GVRD rainfall.

The update considers extreme rainfall recorded at twelve precipitation gauges located throughout the GVRD for two measures: rate of rainfall (intensity) and how often large events occur (threshold exceedance). Firm conclusions about trends are not possible because records are too short and stations are located in disparate locations. In addition, there are large data gaps that may skew some results. A cautious consideration of uncertainty also guides interpretation of the results in sections that address effect on GVRD rainfall of climate variability and climate change. Despite the limitations, results provide an update for planning that depends on GVRD rainfall variability and change as well as a discussion of potential opportunities for future work. An overview of findings is as follows:

Recent trends and patterns

In general, patterns of increased rainfall, as noted in KWL-02, are still occurring and many have become more accentuated since 2001. Statistically significant trends were found at some stations, particularly in April to June, and to a lesser extent October to January. At the station where the most significant trends (DN25 North Vancouver) were found, the largest trends were those with shortest durations.

Climate variability

The potential relationship between known aspects of climate variability and GVRD rainfall was investigated. Larger rainfall events appeared to occur during the positive (warm) phase of the PDO. However, separating this from the underlying long-term trend was beyond the scope of this analysis.

Climate change
Future precipitation projections derived from 29 experiments with 7 global climate models show a considerable range in projections for the GVRD region. A large range indicates considerable uncertainty. However, models consistently project a 14% to 33% decrease in summer precipitation by the middle of the century. In addition, most models project small increases in precipitation during all other seasons, particularly in winter (4% to 14% increase by the middle of the century).

The projected net annual increase in precipitation of 1% to 5% by the middle of the century is too small (and uncertain) to be used for planning purposes. The small range indicates that neither very large decreases nor increases in the annual average are to be expected. However, important seasonal changes are projected despite the small annual average change: large winter precipitation increases (4% to 14%) and summer decreases (-33% to -14%) by the middle of the century. Furthermore, consistent projections for warming in the region by mid-century (2.1°C to 2.6°C) will cause increased winter and spring rainfall due to a larger fraction of total precipitation falling as rain rather than snow.

An overview of recommendations for future updates and further analysis is as follows:

Data quality and local station limitations
- continue using recently digitized data
- fill missing values
- use rehabilitated data
- analyse regionally-averaged results beyond the GVRD to allow for identification of more climatologically robust regional trends (and to include a larger number of stations)

Methods: beyond rainfall intensity and exceedance
- assess vulnerability to rainfall changes, climate change and extreme events
- conduct literature review prior to routine updating to ensure the study of most useful parameters, use of most appropriate research methods, and to understand the limitations
- investigate changes to synoptic weather types[1]
- include snow and temperature trends and projections in addition to rainfall
- event-based analysis as a foundation for examining rainfall and streamflow record
- hydrologic modelling
- apply trend analysis to seasonal results rather than grouping monthly trends by season
- use consecutive water years rather than calendar years and a quantitative comparison of the wet and dry seasons
- select exceedance thresholds using percentiles

[1] Synoptic weather type refers to classification of weather patterns into categories.

List of abbreviations

AHCCD	Adjusted Historical Canadian Climate Data station record
AMRI	Annual maximum rainfall intensity
ATEC	Annual threshold exceedance frequency
CGCM	Canadian Global Climate Model
ENSO	El Niño Southern Oscillation (El Niño/La Niña)
GCM	Global Climate Model / Global Circulation Model
GVRD	Greater Vancouver Regional District
IPCC	Intergovernmental Panel on Climate Change
KWL	Kerr Wood Leidal Associates Ltd.
KWL-02	Previous precipitation report completed by KWL in 2002
MMRI	Monthly maximum rainfall intensity
MSC	Meteorological Service of Canada
MTEC	Monthly threshold exceedance
NSC	Not significant change
NSD	Not sufficient data
OOP	Out-of-phase between winter and summer cumulative departures
PCIC	Pacific Climate Impacts Consortium www.pacificclimate.org
PDO	Pacific Decadal Oscillation
SMMRI	Seasonal monthly maximum grouping of rainfall intensity
SMRI	Seasonal maximum rainfall intensity
SMTEC	Seasonal monthly grouping of threshold exceedance frequency
SRES	Special report on emissions scenarios
STEC	Seasonal threshold exceedance frequency
SWRI	Summer/Winter rainfall intensity
TSEC	Time series, monthly threshold exceedance frequency
TSRI	Time series, monthly rainfall intensity

1 Introduction

1.1 Background

Increased extreme events including more frequent intense rainfall are a possible consequence of global climate change (Easterling *et al.* 2000). Examples of impacts of intense rainfall include flooding and landslides. Recent studies on the rate and occurrence of extreme rainfall events illustrate trends and patterns of increased rainfall across much of the globe (Trenberth 2005). In addition, it is important to extract as much information as possible from historical records for future planning purposes to avoid the underestimation of climate variability (see Hamlet 2003).

In this context, the Greater Vancouver Regional District (GVRD) commissioned a study in 2002 by Kerr Wood Liedal Associates Ltd. (KWL) to examine historical trends in intensity and frequency of rainfall with duration from 5 minutes to 24 hours as recorded at selected rain gauges located throughout the GVRD. This report is hereafter referred to as 'KWL-02'. The findings were also published in a peer-reviewed journal, the Canadian Water Resources Journal (Jakob *et al.* 2003).

KWL-02 found that:

- variability of rainfall events is driven in part by PDO and ENSO cycles
- a cool phase of the PDO (a reversal of the warm phase that has been occurring since 1977) may have started after ~1998 or ~1999
- a PDO reversal could affect rainfall intensity
- analysis of high intensity rainfall threshold exceedance showed increasing trends since the last cool phase (1947-1976) of the PDO
- statistically significant upward trends in rainfall intensity were observed for April, May and June months, especially for shorter duration trends (up to 2 hours)

Since the publication of the report, additional data has been collected by both the GVRD and the Meteorological Service of Canada (MSC). Selected stations were updated with new information spanning the time period from 2002 to 2005. As well, additional historical data has become available in the required format. An outline of all data updated and analysed in this report is included in Appendix B.

1.2 Study Area

The study area comprises the GVRD. Figure 1.1 shows a map of the stations and their annual rainfall amounts. Table 1.1 provides additional details about the stations. Temperatures recorded at the Vancouver Airport average from 3.3°C in January to 17.5°C in July, based on the 1971-2000 climate normal. Average rainfall differs across the GVRD, as shown in Table 1.1 and Figure 1.2. GVRD stations receive most of their precipitation during winter. Hence, in summer and early fall, when demand is at its greatest, the annual hydrograph is at its lowest point. Note also the correspondence between elevation and rainfall throughout the GVRD. For example, DN25 and DN15/82, at elevations of 132m and 156.5m, have the highest rainfall, while YVR, at 4m, receives the lowest amount of rainfall compared to the rest of the stations.

Figure 1.1 Map of rainfall station locations in the GVRD and annual mean rainfall amounts.

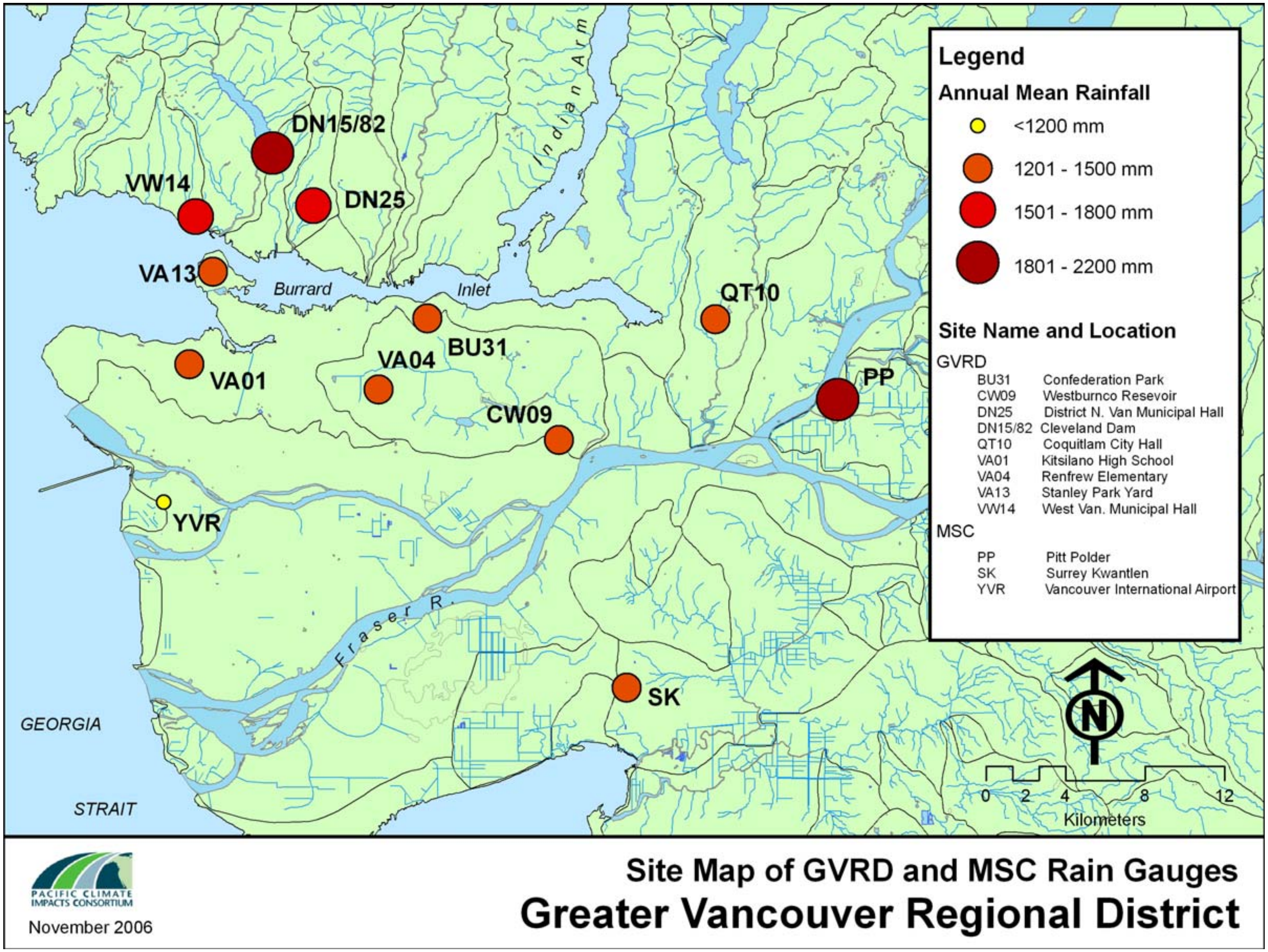
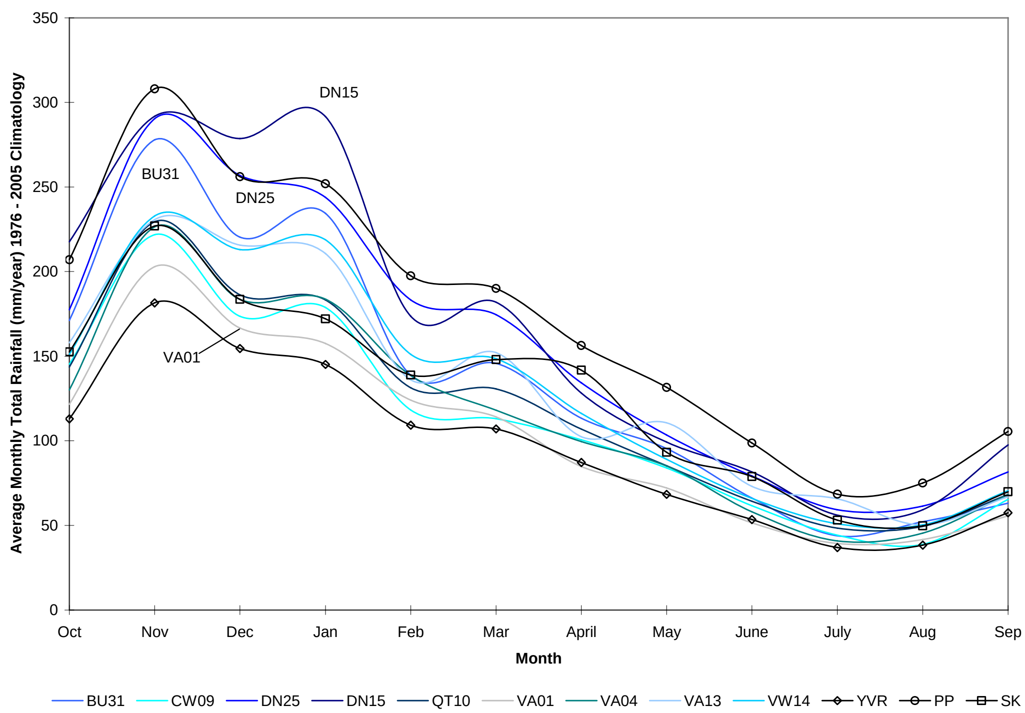


Table 1.1 Station location, elevation, and annual total rainfall

Station	Station Location	UTM Easting	UTM Northing	Elevation (m)	Annual Total Rainfall 1950-2005 (mm/year)	Annual Total Rainfall 1976-2005 (mm/year)	Number of years available 1976-2005
BU31	Confederation Park	500 161	5 458 953	101.0	1 350	1 520	16
CW09	Westburnco Reservoir	506 775	5 452 842	126.5	1 319	1 319	26
DN25	District N. Van Municipal Hall	494 420	5 464 630	132.0	1 757	1 755	30
DN15/82	Cleveland Dam	492 360	5 467 280	156.5	1 847	1 847	13
QT10	Coquitlam City Hall	514 648	5 458 921	26.7	1 477	1 418	30
VA01	Kitsilano High School	488 177	5 456 650	63.0	1 255	1 222	28
VA04	Renfrew Elementary	497 695	5 455 372	88.4	1 366	1 321	30
VA13	Stanley Park Yard	489 362	5 461 300	19.8	1 453	1 508	23
VW14	West Van. Municipal Hall	488 500	5 464 080	40.0	1 622	2 039	30
PP	Pitt Polder	520 811	5 454 862	5.0	2 140	1 433	29
SK	Surrey Kwantlen	510 193	5 440 366	78.0	1 430	1 141	29
YVR	Vancouver International Airport	4868 87	5 449 705	4.0	1 121	1 520	16

Figure 1.2 Monthly total rainfall, October to September for the GVRD stations and MSC stations, 1976–2005.



1.3 Project Purpose and Objectives

Improved understanding of changes to rainfall patterns will assist GVRD staff in planning strategies to adapt to climate change and variability. The purpose of this work is primarily to update some of the KWL-02 rainfall analysis with additional data that was not available at the time of that report. Specifically, KWL-02 attempted to answer the following two questions:

i) Are there trends in rainfall intensity in the GVRD?
ii) Are there trends in rainfall threshold exceedance in the GVRD?

In addition to updating some of the analysis, the methodology used has been documented to aid in further work. Recommendations have also been made about other techniques and tools that may guide future investigations.

Note that this update:

- is not intended to be a complete re-analysis of all of the data and methods used previously in KWL-02
- is not an attempt at a comprehensive analysis of GVRD rainfall (such a study should begin with a literature review to consider other possible analysis methods)
- is intended to address whether additional data, using a similar methodology to KWL-02, indicates trends consistent with the original report.

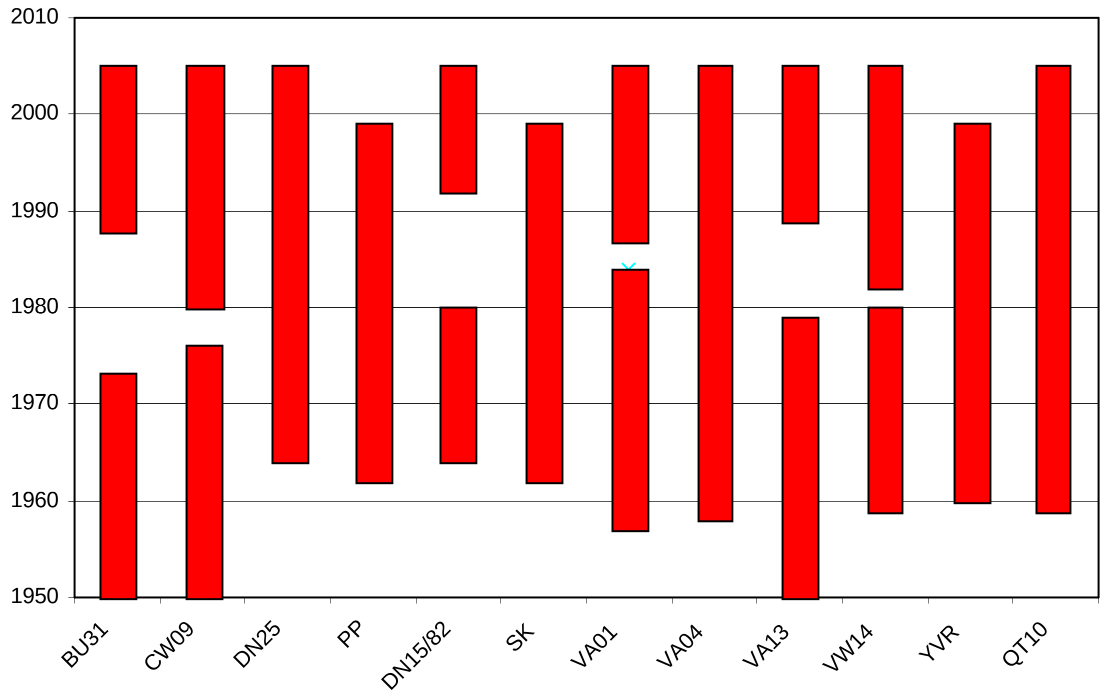
2 Data and Methods

2.1 Historical Rainfall Records

In general, total rainfall, intensity durations, and exceedances were updated at GVRD stations for 2002 to 2005, with some exceptions as listed in the Appendices. The MSC stations update included information on total rainfall amounts only, not intensities. Note that a detailed analysis of shifts in data that could be due to site-specific conditions (i.e. station movements or adjustments; see Appendix C) has not been made. Future work could include cumulative departure plots of data to nearby Adjusted Historical Canadian Climate Data station records (AHCCD, Mekis and Hogg 1999).

Available data are shown schematically in Figure 2.1. A complete accounting of the original records used in the KWL-02 report and the updated station data is listed in Table B1 in Appendix B. Table B2 also includes additional details such as specific time periods and durations as well as notes regarding difficulties using records from certain stations, such as gaps in the record or short total record length.

Figure 2.1 Plots of time periods used in the annual time series analysis. Gaps indicate missing or unavailable data.



2.2 Data Derived from Historical Rainfall Records

Several time series were derived from the rainfall records. Amount of rainfall that occurred was analysed in terms of both **rainfall intensity** and **rainfall threshold exceedance counts**, each described in more detail below.

The time series, consisting of one value for each station, were constructed from available data between 1950 and 2005, for each month independently. In other words, there is a data value for each year from 1950 to 2005 of the maximum rainfall intensity (mm/hr) of a given duration or count of exceedances of a certain threshold (#) that occurs in the given month. Data were also grouped into seasons, as described below.

Historical Rainfall Intensity

All rainfall intensities analysed in this report are maximum intensities. The durations used are 5, 10, 15, 30 minutes, 1, 2, 6, 12 and 24 hour. Note that not all durations were analysed in all cases and that intensities are reported in mm/hr regardless of duration.

For an illustration of rainfall intensity by duration consider the following hypothetical day of rainfall: no rain until 09:03 am at which time the following rain falls, and no further rain falls during the rest of the day:

09:03 – 09:07 6 mm
09:08 – 09:12 5 mm
09:13 – 09:17 2 mm

The maximum rainfall intensity for each duration of this day is calculated as follows.

Table 2.1 Maximum rainfall intensity for hypothetical rain day

Duration	**5 min**	**10 min**	**15 min**	**30 min**	**1 hr**	**2 hr**	**6 hr**	**12 hr**	**24 hr**
Maximum Rainfall (mm)	6	11	13	13	13	13	13	13	13
Maximum Rainfall Intensity (mm/hr)	72	66	52	26	13	6.5	2.2	1.1	0.5

Historical Rainfall Intensity Parameters

- TSRI: time series of monthly maximum rainfall intensity (raw data)
- MMRI: monthly maximum rainfall intensity that occurred in a given month
- SMMRI: grouping of MMRI results by season (winter: Jan, Feb, Mar; spring: Apr, May, Jun; summer: Jul, Aug, Sept; fall: Oct, Nov, Dec). Note: in these cases, the seasonal maximum of the monthly maximums is not taken; the results for individual months are simply displayed together.
- AMRI: annual maximum value of the rainfall intensities for the calendar year
- SWRI: summer/winter difference between the sum of the monthly maximum rainfall intensities from April to September (dry season) and the sum of the monthly maximum intensities from January to March and October to December (wet season) of the calendar year. Note: this definition takes maximums from months that are not in consecutive wet seasons.

Historical Rainfall Threshold Exceedance

Exceedance calculations were run on 5-minute rainfall data and processed using the ExceedCount program, as outlined by KWL-02 and described in detail in a memo to GVRD (KWL 2006). ExceedCount will count each exceedance that occurs, including when a threshold value was exceeded more than once within one day. Thus threshold exceedance is a measure of the frequency of occurrence of large rainfall intensities. MSC stations and some GVRD stations (DN15/82) were not included in the update due to insufficient or unavailable data.

Table 2.2 shows the rainfall intensity thresholds that were used to determine whether or not an exceedance occurred. Typically, a fixed percentile such as the 90th or 95th percentile would be used (Groisman *et al.* 2005), but these thresholds were determined empirically (KWL-02) in order to apply consistent thresholds across different stations and still capture enough data to observe a change in exceedance.

Table 2.2 Rainfall exceedance thresholds from KWL-02

Duration	**5 min**	**10 min**	**15 min**	**30 min**	**1 hr**	**2 hr**	**6 hr**	**12 hr**	**24 hr**
Threshold (mm/hr)	10	10	10	10	6	6	3	2	2

The hypothetical rain day shown above (Table 2.1) would result in one exceedance count at each of the 5 min, 10 min, 15 min, 30 min, 1 hr, and 2 hr durations.

Historical Rainfall Threshold Exceedance Count Parameters

- TSEC: time series of monthly total threshold exceedance counts (raw data)

- MTEC: monthly threshold exceedance counts is the number of times per month that the threshold was exceeded
- SMTEC: grouping of MTEC results by season (winter: January, February, March; spring: April, May, June; summer: July, August, September; fall: October, November, December). Note: in these cases, the seasonal total of the monthly exceedances is not taken; the results for individual months are simply displayed together.
- STEC: seasonal threshold exceedance counts is the number of times per season the threshold was exceeded in winter (January, February, March), spring (April, May, June), summer (July, August, September), and fall (October, November, December)
- ATEC: annual threshold exceedance counts is the number of times per year the threshold was exceeded

Note that although monthly exceedance data was assembled, analysis was restricted to seasonal and annual trends due to insufficient occurrences in the monthly time series to compute trends.

2.3 ENSO and PDO Indices

Indices of the strength of ENSO and PDO were used to examine the influence of large-scale oscillations on variability in rainfall threshold exceedance within the GVRD. El Niño/Southern Oscillation (ENSO) strength can be measured by the Southern Oscillation Index (SOI). In particular, the SOI dataset applied in this analysis was the same as that used in KWL-02[2]. Another common source of the SOI index is the Climate Prediction Centre[3].

The Pacific Decadal Oscillation (PDO) index data was obtained from the Joint Institute for the Study of Atmosphere and Ocean (JISAO)[4]. As was done in KWL-02, both PDO and SOI indices were averaged and standardized based on 1950 onward. A robust method of analysing ENSO and PDO variability has recently been developed for temperature, precipitation, and streamflow (Fleming *et al.* 2007). This method was not applied in this report, however may be a consideration for future work.

2.4 Statistical Analysis

Historical Linear Trends

For this update, simple regression techniques were employed to analyze MMRI (also displayed as SMMRI), AMRI, MTEC (also displayed as SMTEC), STEC, and ATEC. The trend analysis applied uses a non-parametric Mann-Kendall test for trend and Sen's linear slope estimates (Gilbert 1987).

Non-parametric measures assume a non-normal distribution, and therefore allows for statistical inference on these non-normal data sets. The MAKESENS EXCEL spreadsheet template[5] was applied to calculate trends for annual data in all periods, and monthly maximums for the 5 and 15 minute and the 1 and 6 hour durations.

[2] http://www.bom.gov.au/climate/current/soihtm1.shtml
[3] http://www.cpc.noaa.gov/data/indices/
[4] http://jisao.washington.edu/pdo/PDO.latest
[5] http://www.fmi.fi/organization/contacts_25.html

The Sen's method uses a linear model to estimate the slope of the trend. Although not always true for the time series used in this analysis, the method assumes that variance of the residuals is constant in time. Missing values are allowed and the data need not conform to any particular distribution. As well, the Sen's method is not greatly affected by single data errors or outliers.

Statistical Significance of Historical Trends

For a trend to be statistically significant, it must be greater than the year-to-year variability at the particular station. When the probability of a trend being at least correct in sign is less than 10% (or p-value<0.10) then the trend is statistically significant from zero at the 90% level, and so on for the other levels of statistical significance.

Note that significance is a statistical measure that pertains to the likelihood of a trend arising from a given record by chance. When a trend is significant, the trend will stand out above the variability; whether or not the record is long enough to adequately reflect the variability is a separate consideration. Furthermore, statistical significance is not necessarily an indication that a past trend will continue.

Missing Data Points

Some stations included missing values. The Sen's method of trend analysis applied in this study allows for missing values. In the cases where less than 30 years of data was available, the station is considered unsuitable for analysis or interpretation. These cases are noted throughout the report. A summary table for all the data collected and analyzed in the report is provided in Appendix B.

Comparison of Means by PDO period

For annual exceedance, a comparison of means (average change) between the exceedance counts from the pre-76/77 to post-76/77 period was performed. Stations BU31, DN25, VA01, VA04, VA13, and QT10 were used for this analysis. The remaining stations had insufficient records to perform the comparison.

2.5 Visual Analysis

Figures were produced for TSRI, SMMRI, AMRI, SWRI, TSEC, SMTEC, and ATEC. Rainfall intensities figures show different combination of raw data, smoothed data, simple linear regression lines, and cumulative departures from the mean. Exceedance figures consist of bar or line graphs only.

TSRI figures show raw data, a linear trend line, smoothed data (12-month running average), and the cumulative departure. All durations are shown.

SMMRI figures show the month-by-month values in monthly triplets: January-February-March, April-May-June, July-August-September, October-November-December. Raw data and smoothed data (12-year running average) are shown for four durations.

AMRI figures show raw data, a linear trend line, smoothed data (5-year running average), and the cumulative departure. All durations are shown.

SWRI figures show cumulative departures, offering a comparison of the difference in phases of the summer and winter seasonal maximums. All durations are shown.

TSEC figures show smoothed data (12-month running average) for comparison to PDO and ENSO indices. TSEC and both indices are all standardized before smoothing. Four durations are shown.

SMTEC figures show the month-by-month values in monthly triplets: January-February-March, April-May-June, July-August-September, October-November-December. Raw data and smoothed data (12-year running average) are shown for four durations.

ATEC figures show raw data with a bar graph. All durations are shown.

Linear trend for visual analysis

The linear trends shown in all of the figures described above do not use the Sen's method described in statistical analysis above. Thus, trend lines may not yield exactly the same result as those computed using the statistically robust analysis tools. For the purposes of the visual analysis, the simple linear trend line (included with EXCEL) is shown on the graphs.

Smoothed data

Smoothing was applied to the figures described above with either a 5-year, 12-year, or 12-month moving average window.

Cumulative Departure from the Mean

Cumulative departure from the mean was used to determine monthly, annual, winter and summer deviations from the long term average (1950-2005).

2.6 Recent Extreme Events

The question of whether extreme events are possible indicators of climate change is beyond the scope of this report. However, a short list of notable recent weather events in the GVRD during the update period (2002-2005) includes:

- May 2002: High snow-pack levels, rapid melting and heavy rainfall caused severe runoff and flooding in many areas of B.C. except Vancouver Island and the Central Coast. The spring freshet caused significant damage to private properties, public transportation corridors, and recreation facilities. (Source Provincial Emergency Program Canadian Disaster Database)
- October 17 – 24th, 2003: A storm system aided by a powerful Pacific jet stream brought heavy rains and flooding to areas of Washington and British Columbia during mid October. In British Columbia, rainfall was described as the heaviest in 100 years, with around 500 mm (16 inches) of rain falling over an eight-day period in the Pemberton and Squamish region[6]. Flooding took out the Rutherford Bridge and rail

[6] http://www.ncdc.noaa.gov/oa/climate/research/2003/oct/hazards.html

line, displaced hundreds of people from homes in Squamish, Pemberton and Whistler corridor region. Five people lost their lives.

- January 2005: A warm, moist rainfall event known as a tropical punch, hit the southwestern part of BC on Sunday January 16th, 2005 (Wikinews 2005). In the 48 hours leading up to Wednesday January 19, 2005 more than 320 mm of rain fell in the Mt Seymour area (NRCAN 2005). At 3:15 am on January 19, 2005 a landslide of mud, debris and snow destroyed two homes and killed one person near the Seymour River in North Vancouver (NRCAN 2005, Whyte 2006). The heavy rainfall continued over a five-day period from January 16th to 20th, 2005 and temperatures warmed approximately 12°C, which melted existing snow and contributed to large runoff volumes (DPM 2005). Variation in rainfall over the GVRD area is evident from the reports of only 130 mm of rain falling in Vancouver proper in the three-day period preceding the landslide (NOAA 2005) and 240 mm of rain falling in Pitt Meadows over the whole five-day period (DPM 2005), versus the 320 mm measured on Mt Seymour over only two days.

In addition, several records were broken in the period that occurred after 2005. For example, the record number of days of rain in one month was broken in January 2006, and several major rainfall and wind events battered the GVRD from November 2006 through January 2007. In November, rainfall in excess of 150 mm occurred within a 15-hour period; this triggered erosion in GVRD watersheds that caused temporarily elevated levels of turbidity, leading to a boil-water advisory that, at times, impacted the majority of the region's residents.

2.7 Removal of Outliers

The January 2005 event was the largest of those listed above that occurred within the 2002-2005 update period. Because outliers that fall at the end of a time series may skew results, further examination was undertaken to understand the amount of influence on trends. In order to test the effect of this event, it was excluded from trend analysis, and data was re-analysed (see Table 3.3).

It should be noted, however, that the January 2005 event only appears extreme at one rainfall station (QT10) for rainfall intensities of 5 minutes to 2 hours, despite causing significant flooding in regions of the GVRD, particularly in North Vancouver. For threshold exceedance, on the other hand, the event appears extreme for BU31, CW09, and VA04, but none of these stations are located in North Vancouver.

While rainfall intensity and threshold frequency are important features of rainfall leading up to flooding events, there are alternate factors that generate flooding. Examples include pre-event soil moisture, occurrence of rain-on-snow, number of consecutive days of rain, total amount of recent rainfall, runoff conditions, imperviousness, tidal conditions, storm surge, sea level and infrastructure engineering. The need to understand the spatial and meteorological context of events that cause flooding in the GVRD is discussed further in Section 5.

3 Results and Discussion

In this section, results of linear trend analysis are shown and discussion is provided along with visual analysis (graphs). An overview is followed by detailed results. Note that trends are computed as a slope per year and have been converted, in some cases, to per century. However, the trend does not represent the change that has occurred over the entire 20th century because all records used for this analysis begin in 1950 or later. Results reported in a less technical document should be expressed as per 50 years or per decade to avoid potential misinterpretation of the trend magnitude.

3.1 Historical Rainfall Intensity

3.1.1 Overview of Rainfall Intensity Trends

On an **annual** basis, less than half of the rainfall intensity trends are statistically significant (Table 3.1) on average across all durations,. Trends that are significant are generally slight increases, and tend to occur for only a few durations for most stations. There are few negative trends, they tend to be smaller in magnitude, and none are statistically significant.

Table 3.1 Summary table of AMRI, SMRI and SWRI trends

Stations	**Annual (AMRI)**			**Seasonal (SMRI)**				**Out of Phase (SWRI)**
	5, 10, 15 min	*0.5, 1, 2 hr*	*6, 12, 24 hr*	*Fall*	*Winter*	*Spring*	*Summer*	*Fall-Winter/ Summer-Spring*
BU31	**P**	**P**	**P**	**P, P, P**	**P**, nt^p, **P**	nt^p, **P**, p	nt^p, nt, **P**	None
CW09	nt^p	p	nt^p	nt^n, nt, **N**	nt^p, **N**, nt^p	nt^p, p, nt^p	nt^p, n, **N**	5-15min, 2-24hr
DN25	**P**	**P**	p	nt^p, **P**, **P**	**P**, n, **P**	p, **P**, **P**	nt^p, nt^p, nt^p	None
DN15/82	nt^p	nt^n	nt^n	nt^n, nt, p	nt^p, n, nt^p	n, n, **P**	**N**, nt^n, nt^n	None
QT10	**P**	p	nt^p	nt^p, nt^p, n	nt^p, **N**, **P**	nt, **P**, nt^p	nt^p, nt^p, nt^n	6-24hr
VA01	nt^p	p	p	nt^p, nt^p, nt^p	nt^p, **N**, **P**	p, p, nt^p	p, n, nt^p	24hr
VA04	nt^p	nt^p	nt^p	nt^p, p, nt^p	n, **N**, nt^p	nt, **P**, nt^p	nt^p, nt^p, nt^p	15-30 min, 12-24 hr
VA13	nt^p	**P**	p	**P**, **P**, p	**P**, nt, nt^p	**P**, **P**, **P**	**P**, nt^p, nt^p	5min-2hr
VW14	nt^p	**P**	nt^p	nt^n, nt^n, **P**	nt^p, **N**, **P**	nt^p, nt^p, **P**	**N**, **N**, nt	None
PP	nt^p	nt^p	nt^n	**P**, p, nt^n	nt^p, n, nt^p	nt^p, p, **P**	nt^p, p, nt^n	5-15min
SK	nt^p	nt^p	nt	**P**, nt^p, p	nt^n, n, n	**P**, **P**, **P**	nt^p, nt^p, nt^n	12hr
YVR	**P**	**P**	nt^p	nt^p, **P**, **P**	nt^p, nt^p, nt^p	**P**, p, **P**	nt^p, p, nt	2-24hr
DN25[a]	**P**	**P**	nt^p	n/c	n/c	n/c	n/c	n/c
QT10[a]	**P**	nt^p	nt^p	n/c	n/c	n/c	n/c	n/c

Fall = October, November, December
Winter = January, February, March
Spring = April, May, June
Summer = July, August, September
[a]Alternate years used (see Section 3.1.2)

P = Positive and > 95%
p = Positive and > 90%
nt^p = Positive trend < 90%
nt^n = Negative trend < 90%
nt = No trend neutral, or opposing signs < 90%
n = Negative and > 90%
N = Negative and > 95%
n/c = Not calculated

Seasonally, a greater number of significant trends are found with some tendency towards negative trends. Trends are generally positive in fall and spring, with the greatest number of positive trends found in the spring months (April, May and June). Summer months have few significant trends. In winter both positive and negative significant trends occur – in some cases the same station has trends of opposite sign in different months of the winter. Detailed monthly trends are shown in Table 3.4.

Visual analysis of SWRI (not shown) indicates that wet (October – March) and dry season (April – September) cumulative departures are out of phase at 8 of the 12 stations for at least one duration (although no particular duration is out of phase at more than a small number of stations). This result occurs even in cases with few significant trends in the individual months. Thus, a trend towards increasing rainfall intensities for the dry season is accompanied by a decrease during the wet season and vice versa for those cases (KWL-02). Further analysis of SWRI should consider consecutive wet years rather than calendar years and a quantitative comparison of the wet and dry seasons.

Table 3.2 Summary of TSRI cumulative departures from the mean for all stations

Stations	Monthly	Direction	Annual	Direction
BU31	NSD	NSD	NSD	NSD
CW09	1992-1995 1996-1998 2004-2005	- + +	1969-1982 1982-1992 2003-2005	+ - +
DN25	1964-1977 1977-1983 1994-2005	- + +	1964-1977 1994-2005	- -
DN15/82	NSD	NSD	NSD	NSD
QT10	1966-1983 1994-2005	- +	1965-1990	-
VA01	1964-1977 1993-2005	- +	1962-1974 1992-2005	- +
VA04	1972-1980 1987-1995 1995-2001 2001-2005	- - + -	1971-1979 1987-1995	- -
VA13	1995 - 2002	+	NSC	
VW14	1964-1972 1993-1998 1998-2004	- + -	1960-1972 1982-1998	- +
PP*	1995-1999	+	1992-1999	+
SK*	1962-1972 1993-1997	- +	1978-1984	+
YVR*	1964-1977 1995-1999	- +	1962-1990 1995-1999	- +

NSD: Insufficient data to determine a trend
NSC: No systematic changes in the data record
* Data to 2000 only

Rainfall intensity cumulative departures from the mean (TSRI) are summarized in Table 3.2. In this analysis, sequences of years above or below the long-term average are indicated in the table. In general, periods of below average rainfall intensity are observed during the 1960s to the mid-1970s, while periods of above average rainfall intensity are observed for the mid-1990s to present. At VA01 and VW14, this situation reverses to a negative departure until 2005. However, at most (four) of the stations, the period of above average intensity continues into 2005.

In summary, there is some weak, statistically significant evidence for increasing rainfall intensity over time found in AMRI, primarily in the 5-minute to 2-hour periods at 8 out of 12 stations. Statistically significant trends in MMRI are found at more stations during the winter and spring, while summer trends occur only at a few stations. However, trends are relatively weak: statistically significant increases of 10 mm/hr per century or higher are shown in bold in the tables but occur in only 10% of the cases examined.

Note: this threshold is meant as a qualitative aid to interpreting magnitude of change only; since each station has a different climatology and variability the best guide to the relative importance of a trend is its level of statistical significance. Cumulative departures from the normal indicate that periods of lower intensity occurred generally in the early 1960s to the mid-1970s, with mainly above average intensity from the mid-1990s to present. In order to better understand the mechanisms behind the observed changes in rainfall intensity, more in-depth analysis is required.

3.1.2 Detailed Analysis

Rainfall trend analysis (annual) results are given below (Table 3.3) and summarized in Table 3.1. Significant positive trends (increasing intensity) are observed at 8 of the 12 stations examined. Most trends are weak but stations with the largest trends include: BU31, DN25, QT10 and YVR. Most often, the significant trends that are larger than 10 mm/hr per century occur within the 5-30 minute duration rainfall records. The 2 hour duration has significant, although weak, increasing rainfall intensities at six out of 12 stations.

Both DN25 and QT10 were tested using alternative time periods to determine the impact of specific events. At DN25, the installation of a cooling tower in 1994 (discussed and analysed in KWL-02) necessitated checking of rainfall intensity records from the period of record prior to installation of the cooling tower. Prior to 1994, increases in rainfall intensity remain significant and strong in comparison to other findings (20 to 60 mm/hr per century increases for 5 minutes to 30 minute durations, respectively). Even with the installation of the cooling tower, increases to rainfall intensity are occurring at DN25. However, the impact of the cooling tower installation on rainfall intensity cannot be fully understood without undertaking additional work, as outlined in KWL-02.

In the case of QT10, a large rainfall event that occurred at the end of the record (2005) may have skewed records towards an artificially high rainfall intensity trend. However, even with the removal of 2005, the 10-minute rainfall duration events are significant and still 27 mm/hr per century as compared with 31 mm/hr per century with the 2005 record included.

Results of MMRI trend analysis are given in Table 3.4 for four durations: 5 minute, 15 minute, 1 hour and 6 hour (Table 3.1). The monthly trends for all stations and each month are given, including their significance level. The overall count of significant trends (at both the 95 and 90% confidence intervals) is shown in Figure 3.1. The highest number of significant rainfall events occurs in May and June at the 95% level. The month of May had a slightly greater number of significant rainfall events. This result holds at the 90% confidence level as well (Figure 3.1b). If the counts are totaled for each season, the spring season shows the greatest number of significant, positive rainfall events occurring (see lines indicating seasonal totals in Figure 3.1a).

Table 3.3 AMRI trend (mm/hr per century) for all durations

Stations	**5min**	**10min**	**15min**	**30min**	**1hr**	**2hr**	**6hr**	**12hr**	**24hr**
BU31	**34** *	**17** ×	**14** ×	8	7 **	6 **	3 *	2 *	2 ×
CW09	18	20	12	9	4 ×	2	1	0	-1
DN25	**64** **	**44** ***	**36** ***	**19** **	**10** ***	6 **	3	3 ×	1
DN15/82	-8	10	0	-4	-3	0	-1	0	-2
QT10	19	**31** *	15	8	5 ×	2	1	0	0
VA01	22	7	5	6	2	4 *	3 *	0	0
VA04	0	4	0	2	2	3	2	1	0
VA13	15	0	8	3	3	4 *	3 ×	2	1
VW14	12	-95	9	5 ×	5 ×	5 *	2	0	0
PP	48	22	21	11	3	0	-4	-4	NA
SK	7	5	7	6	2	-1	0	-1	NA
YVR	**40** *	22	10	9	5	6 **	1	0	0
DN25a	**61** *	**46** *	**38** *	**20** *	9 *	7 ×	0	0	-2
QT10a	14	**27** ×	11	6	4	1	1	0	0

***	Significant at 99.9%
**	Significant at 99%
*	Significant at 95%
×	Significant at 90%
Bold	>= 10 mm/hr per century and significant
NA	Not available
DN25a/QT10a	Alternate years used (see Section 3.1.2)

The numbers of significant rainfall trends stronger than 10 mm/hr per century are indicated with bold (Table 3.4). These relatively large trends occur most frequently in 5-minute and 15-minute durations and in the spring months of April, May and June. The strongest of these are occurring in the 5-minute duration during June. Also of note are the 5-minute rainfall trends occurring in October at PP and SK. MMRI decreased in February, with negative trends for the 1 and 6 hour durations.

Figure 3.1 Distribution of months with positive trends that are significant at the (a) 95%, and (b) 90% level for MMRI. Lines indicate seasonal groupings for winter, spring, summer and fall.

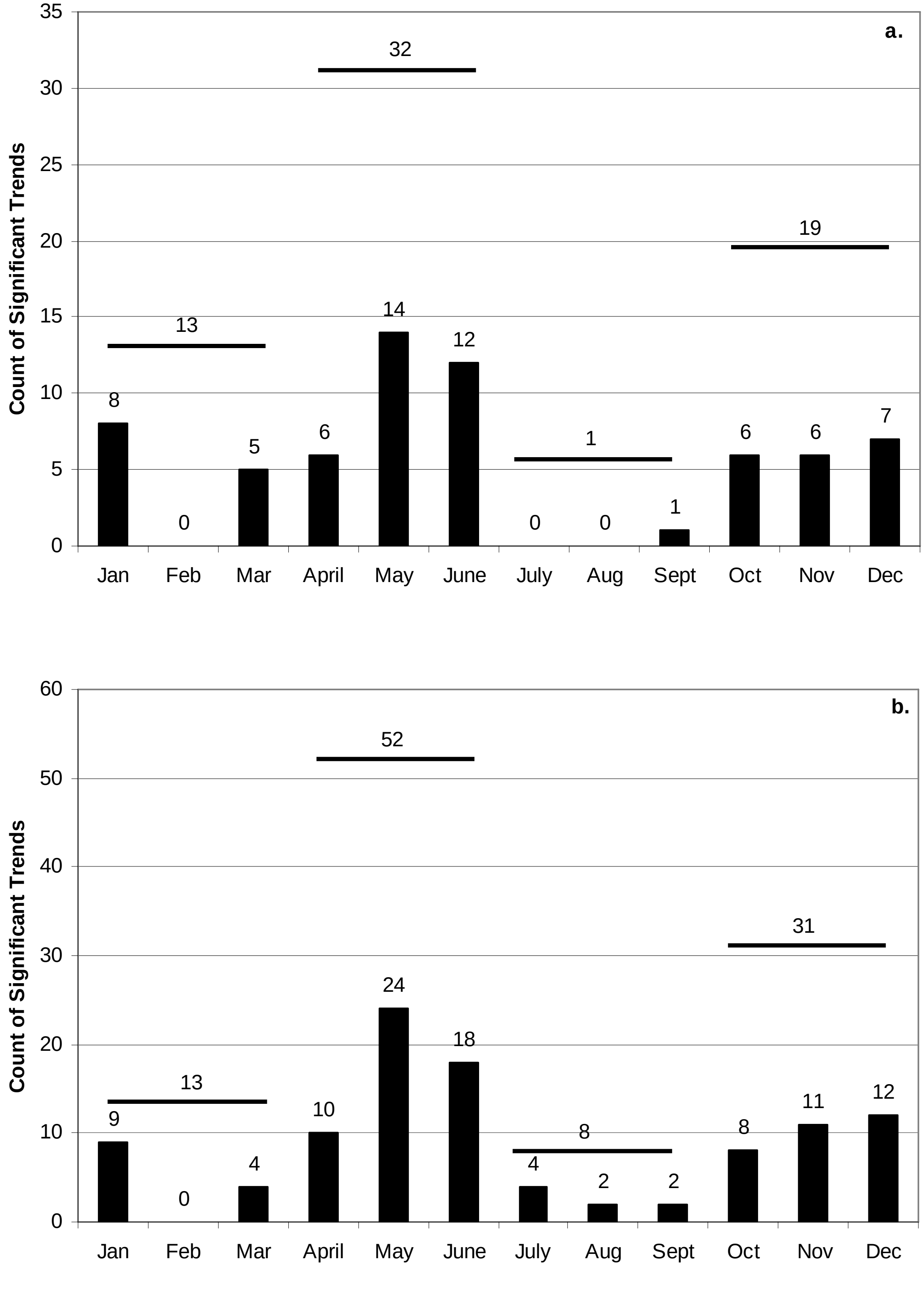


Table 3.4a-3.4l MMRI trend analysis for monthly values January – December. Values in bold are significant and trends are >= .10 mm/hr per year (10 mm/hr per century) over the period of record. Statistical significance is indicated in the column preceding the trend.

a. January

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	**	**0.13**	**	0.08	**	0.05	**	0.04
	CW09		0.00		0.00		0.00		-0.01
	DN25		0.06		0.07	*	0.06		0.04
	DN1582		0.00		0.03		0.04		0.02
	QT10		0.00		0.00		0.00		-0.09
	VA01		0.00		0.01		0.00		-0.02
	VA04		0.00	×	-0.07		-0.04		-0.08
	VA13	×	0.03	**	0.05	**	0.04	*	0.02
	VW14		0.00		0.00		0.00		0.00
MSC	PP		0.00		0.00		0.00		0.00
	SK		0.10		0.00		0.01		0.01
	YVR		0.00		0.00		0.00		-0.01

b. February

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31		0.00		0.00		0.00		0.00
	CW09		0.00		-0.03		-0.02	**	-0.03
	DN25		0.00		0.00		-0.04	×	-0.04
	DN1582		-0.02		-0.04	×	-0.06		-0.03
	QT10		0.00		0.00		-0.02	**	-0.03
	VA01		0.00	*	-0.05	*	-0.04	×	-0.02
	VA04		0.00	*	-0.05	**	-0.04	**	-0.03
	VA13		0.00		0.00		-0.01		-0.01
	VW14	**	**-0.11**	***	**-0.10**	***	-0.07	***	-0.05
MSC	PP		0.13		0.02		-0.04	×	-0.04
	SK		0.05		0.01		0.00	×	-0.03
	YVR		0.00		0.02		0.00		-0.01

c. March

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	**	**0.11**	**	0.08	*	0.04		0.01
	CW09		0.00		0.01		0.01		0.00
	DN25		0.00		0.02	×	0.03	×	0.02
	DN1582		0.02		0.03		0.02		0.01
	QT10		0.00		0.02	*	0.04		0.02
	VA01		0.00		0.00		0.02	×	0.02
	VA04		0.00		0.00		0.00		0.00
	VA13		0.00		0.01		0.00		0.00
	VW14		0.05	×	0.05	*	0.03		-0.01
MSC	PP		0.10		0.04		0.05		0.00
	SK		0.00		-0.04		0.00	×	-0.03
	YVR		0.08		0.07		0.02		0.00

***	Significant at 99.9%
**	Significant at 99%
*	Significant at 95%
×	Significant at 0.10 or 90%
Bold	>= .10 mm/hr per year and significant

d. April

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31		0.02		0.03		0.02		0.01
	CW09		0.02		0.04		0.01		-0.03
	DN25	×	**0.16**		0.05		0.03		0.01
	DN1582		-0.04		-0.03		-0.02	×	-0.03
	QT10		0.00		0.00		-0.01		-0.00
	VA01		0.10	×	0.05		0.02		0.01
	VA04		0.01		0.03		-0.01		-0.01
	VA13	**	**0.11**	**	0.08	*	0.03		0.01
	VW14		0.08		0.06		0.00		-0.02
MSC	PP		0.15		0.00		-0.04		0.00
	SK	*	**0.20**	*	**0.14**	×	0.05		0.00
	YVR	×	**0.20**		0.06	*	0.06		0.02

e. May

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	×	**0.15**	×	**0.10**	**	0.06	*	0.02
	CW09	×	**0.15**	×	0.08	×	0.04		-0.01
	DN25	×	**0.18**		0.13	*	0.07		0.00
	DN1582		0.05		0.05		0.05	×	-0.04
	QT10	**	**0.23**	**	**0.15**	**	0.06		0.01
	VA01	×	**0.10**	×	0.065		0.03		0.00
	VA04	**	**0.23**	*	**0.12**	***	0.07	×	0.02
	VA13	**	**0.18**	***	**0.13**	**	0.06		0.01
	VW14		0.08		0.06	*	0.05		-0.00
MSC	PP		0.24		0.17	×	**0.12**		0.03
	SK		0.08		0.08	*	0.07		0.08
	YVR	×	0.26		0.11	×	0.04		-0.00

f. June

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	×	**0.23**		0.10		0.04		0.01
	CW09		0.03		0.06		0.00		-0.02
	DN25	**	**0.42**	*	**0.20**	*	**0.10**		0.01
	DN1582	*	**0.25**	×	**0.14**		0.04		-0.01
	QT10		0.00		0.06		0.01		0.01
	VA01		0.11		0.08		0.04		0.01
	VA04		0.00		0.01		0.07		0.01
	VA13	*	**0.15**	×	0.07		0.03		0.01
	VW14	*	**0.37**	*	**0.27**		0.05	×	-0.03
MSC	PP	**	**0.71**	*	**0.32**		0.08		-0.01
	SK	**	**0.40**	×	**0.20**		0.07	×	0.03
	YVR	×	**0.26**	*	**0.17**	*	0.08		0.02

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
Bold >= .10 mm/hr per year and significant

g. July

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31		0.00		0.00		0.03		0.02
	CW09		0.00		0.00		0.02		-0.03
	DN25		0.00		0.00		-0.01		0.01
	DN1582		-0.07		-0.02		-0.01	*	-0.04
	QT10		0.05		0.04		0.01		0.01
	VA01	×	**0.15**		0.08		0.04		0.01
	VA04		0.00		0.00		0.01		0.00
	VA13	×	**0.17**		0.08	×	0.06	×	0.02
	VW14		-0.14		-0.06		0.00	*	-0.06
MSC	PP		0.00		0.00		0.00		-0.02
	SK		0.00		0.05		0.02		-0.01
	YVR		0.17		0.10		0.04		0.01

h. August

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31		0.00		0.00		-0.02		0.00
	CW09		-0.16		-0.10		-0.05	×	-0.04
	DN25		0.00		0.00		0.00		0.00
	DN1582		-0.30		-0.13		-0.03		-0.03
	QT10		-0.01		0.00		0.00		0.00
	VA01	×	-0.09	×	-0.06		-0.03		-0.01
	VA04		0.08		0.01		0.01		0.00
	VA13		0.00		-0.02		-0.01		-0.01
	VW14	×	**-0.23**	×	**-0.13**		-0.04	**	-0.05
MSC	PP	×	**0.39**		**0.27**		0.08		0.03
	SK		0.17		0.03		0.00		-0.01
	YVR		0.13		0.08	×	0.07		0.02

i. September

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	*	**0.19**	×	**0.11**		0.03		0.00
	CW09		-0.15		-0.10		-0.05	*	-0.05
	DN25		0.08		0.00		0.00		-0.01
	DN1582		-0.04		-0.08		-0.05		-0.04
	QT10		-0.09		-0.02		-0.02		-0.02
	VA01		0.02		0.04		0.02		-0.01
	VA04		0.16		0.10		0.03		-0.01
	VA13		0.09		0.08		0.04		0.02
	VW14		-0.02		-0.02		0.00		-0.03
MSC	PP		0.23		-0.01		-0.03		-0.03
	SK		0.00		-0.11		-0.03		-0.02
	YVR		0.11		0.03		-0.01		-0.02

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
Bold >= .10 mm/hr per year and significant

j. October

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	×	**0.13**	*	**0.11**	×	0.04		0.02
	CW09		-0.04		-0.06		-0.02		0.00
	DN25		0.12		0.06		0.03		0.00
	DN1582		-0.11		-0.02		-0.02		-0.03
	QT10		0.00		0.00		0.00		0.00
	VA01		0.00		0.00		-0.00		0.01
	VA04		0.00		0.05		0.02		-0.00
	VA13		0.00		0.05		0.04	*	0.03
	VW14		-0.00		-0.00		0.01		-0.01
MSC	PP	**	**0.45**	*	**0.19**		0.06		0.01
	SK	*	**0.34**	*	**0.20**		0.03		-0.01
	YVR		0.00		0.05		0.02		0.01

k. November

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	×	0.08	×	0.06	***	0.08	**	0.05
	CW09		-0.01		-0.01		0.00		0.00
	DN25		0.05		0.04	*	0.06	**	0.05
	DN1582		-0.04		-0.04		0.00		0.01
	QT10		0.00		0.00		0.01		0.01
	VA01		0.00		0.03		0.02		0.01
	VA04		0.00		0.00		0.03	×	0.03
	VA13		0.04		0.00	×	0.03	*	0.02
	VW14		-0.07		-0.03		-0.01		0.00
MSC	PP		0.09	×	0.13		0.03		0.01
	SK		0.06		0.00		0.01		0.02
	YVR		0.06		0.04	*	0.06		0.01

l. December

			5 min		***15 min***		***1 hr***		***6 hr***
GVRD	BU31	**	**0.13**	*	0.08	×	0.04		0.01
	CW09		0.06	×	0.06		0.01	*	-0.05
	DN25	**	**0.21**	***	**0.17**	**	0.08		0.03
	DN1582		0.10	×	**0.10**		0.03		0.02
	QT10		0.00		0.00		-0.01	×	-0.03
	VA01		0.07		0.05		0.00		-0.01
	VA04		0.00		0.00		0.00		-0.01
	VA13		0.00	×	0.05		0.01		0.01
	VW14		0.02	*	0.05		0.00		-0.01
MSC	PP		0.00		-0.07		-0.04		-0.04
	SK	×	**0.13**		0.03		0.03		0.01
	YVR	*	**0.12**		0.03		0.02		0.00

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
Bold >= .10 mm/hr per year and significant

3.1.3 Effect of 2002-2005 data update on Historical Rainfall Intensity trends

The effect of data from 2002 to 2005 on rainfall intensity trends was examined. Results are shown in Table 3.5, which may be compared to Table 3.3 (AMRI up to 2005). In general, rainfall trends as observed in KWL-02 are still occurring, and most relationships have become more accentuated since 2001. BU31 and QT10 have stronger trends in rainfall intensity in their 5- and 10-minute rainfall records with the inclusion of the 2005 data. However, VW14's trend to 2001 of 18 mm/hr per century is significant at the 90% confidence interval for the 15-minute duration but the trend is smaller (9 mm/hr per century) and no longer significant with data up to 2005 included. The trend at DN25 is also weaker with data up to 2005.

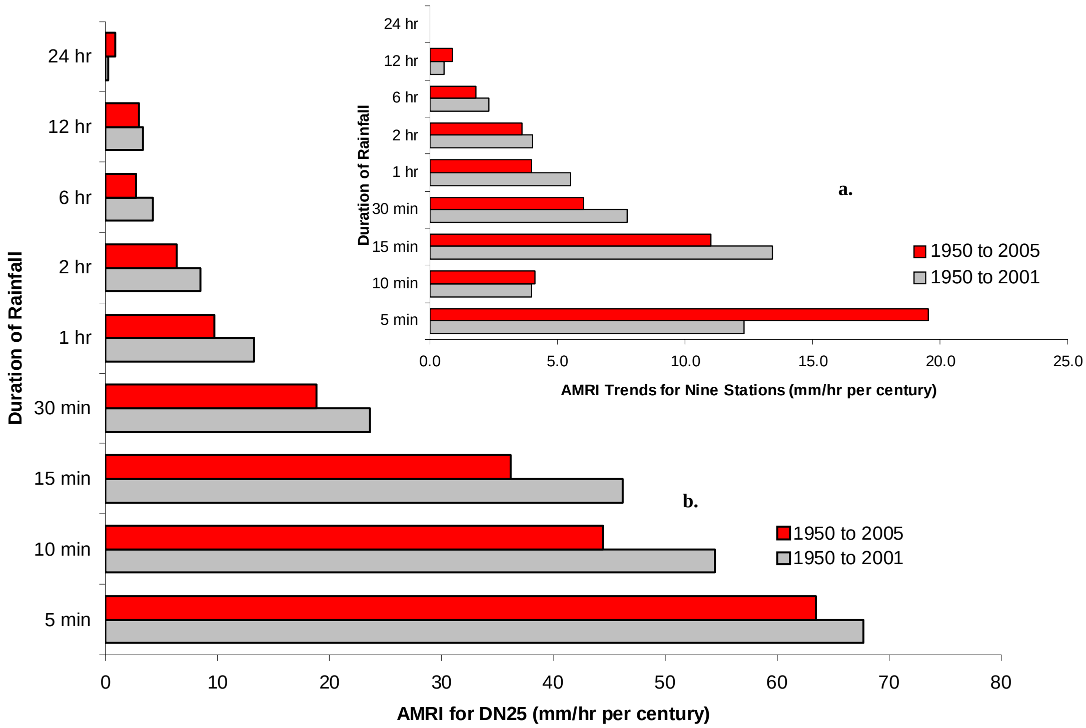
Table 3.5 AMRI trends 1950-2001. Bold values are >= 10 mm/hr per century.

Stations	5min	10min	15min	30min	1hr	2hr	6hr	12hr	24hr
BU31	9	4	8	8	7 *	6 **	3 ×	2	1
CW09	0	28	13	10	6 ×	1	1	-2	-1
DN25	**68 ****	**54 ****	**46** ***	**24** ***	**13** ***	8 **	4 ×	3 ×	0
DN15/82	-30	-8	0	-3	0	0	1	1	-2
QT10	16	20	15	8	5 ×	1	1	-1	-1
VA01	19	8	7	8	4	5 *	2 ×	0	-1
VA04	-8	2	0	0	2	3	2	0	0
VA13	17	0	15	8	6	5 *	3 *	1	0
VW14	20	0	**18** ×	7 *	7 *	5 *	3	0	-1

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
Bold >= 10 mm/hr per century and significant

Figure 3.2a shows the trends of average rainfall intensities for all stations, based on the data from 1950 to 2001 versus the data from 1950 to 2005. Trends have been calculated as a per century value to allow for comparison between the two data periods. The 5-minute duration contains the greatest average change between the two data sets. Figure 3.2b shows differences in rainfall intensities at station DN25 over the two periods. In almost all durations, with the exception of the 24-hour duration, DN25 trends are lower (less rainfall intensity) with the additional data up to 2005.

Figure 3.2 AMRI trends (mm/hr per century) for (a) average of 9 stations (BU31, QT10, CW09, DN25, DN15/82, VA01, VA04, VA13, VW14) and (b) DN25.



3.2 Historical Threshold Exceedance Frequency

3.2.1 Summary of Historical Threshold Exceedance Frequency Trends

In addition to rainfall intensity, analysis of the frequency of events exceeding a specific threshold allows for consideration of not only of the maximum rainfall intensity occurring over time, but also the second, third and n^{th} most intense rainfalls as well. Threshold exceedances analysis counts the number of times a certain rainfall threshold is exceeded over time (see Table 2.1).

Table 3.6 provides an overall summary of the trends in exceedance thresholds. Only stations with available data were analyzed (see Appendix B). Short duration (<2 hours) annual trends are mostly positive. Trends in the longer duration records are weaker. In the annual record positive trends dominate results while only one station (VW14) is overwhelmingly negative. Seasonal trends illustrate the importance of spring increases in rainfall on the positive result that was observed for the annual record. All other seasons have few significant trends.

Table 3.6 Summary of ATEC and STEC trends

Stations	Annual			Seasonal			
	5, 10, 15 min	*30, 1, 2 hr*	*6, 12, 24 hr*	*Winter*	*Spring*	*Summer*	*Fall*
BU31	Positive	Positive	Positive	No trend	Positive	No trend	Positive
CW09	Negative	No trend	No trend	Negative	No trend	Negative	Negative
DN25	Positive	Positive	No trend	No trend	Positive	No trend	Positive
QT10	Negative	Positive	No trend	No trend	Positive	No trend	Negative
VA01	Positive	Positive	No trend	Negative	Positive	No trend	No trend
VA04	No trend	No trend	Negative	Negative	Positive	No trend	No trend
VA13	Positive	Positive	Positive	No trend	Positive	Positive	Positive
VW14	Negative	Negative	Negative	No trend	No trend	Negative	Negative

Visual inspection of rainfall intensity and threshold exceedance time series (not shown) shows peaks of ATEC in the late 1960s, the mid 1970s, the early-1980s, 1991/92, the mid to late 1990s (1996 and 1997/98), and in 2003/2005.

Table 3.7 Years of extreme values of ATEC at selected stations.

Stations	5min	10min	15min	30min	1hr	2hr	6hr	12hr	24hr
BU31	97, 05	97, 95	97, 95	05, 97	95, 05	95, 95	90, 95	90, 95	96, 92
CW09	86, 80	81, 80	86, 81	96, 97	80, 86	80, 05	97, 84	80, 84	86, 98-96
DN25	81, 97	81, 97	81, 97	97, 81	97, 99	97, 99	95	80	97/95
QT10	91	91	81	03	84	03, 86	75, 84	67, 74	98, 59
VA01	96	96	96	96, 04	96	99	71, 96	75, 96	98
VA04	97, 98	97, 01	97, 60	60	05/60/ 61/68	00, 05/68	96, 59/61	90, 98	96
VA13	96	96	96	96, 91	96, 98	88, 91/96	90	90	90
VW14	91	91	91	91	91	91	92	91	91

Two years are shown for most stations, however in some cases only one year stood out. A slash between years indicates the same extreme threshold exceedance value was found in both or multiple years.

3.2.2 Detailed Results of Historical Threshold Exceedance Trends

Table 3.8 and 3.9 show the ATEC and STEC trends. At CW09 and VW14, shorter records (<30 years) skew the results to the more recent years (start date in 1980 for CW09 and 1991 for VW14). Thus, these results should be treated with caution. Appendix B provides detailed information about the records available at each station.

Table 3.8 ATEC trends (# of occurrences per year)

Stations	5min	10min	15min	30min	1hr	2hr	6hr	12hr	24hr
BU31	52 ***	39 ***	28 ***	14 ***	32 ***	13 ***	25 ***	21 ***	8 **
CW09[&]	-175 **	-75 *	-22	0	-14	0	-10	-14	0
DN25	33	23 ×	19 ×	16 **	24 *	6	7	3	0

Stations	**5min**	**10min**	**15min**	**30min**	**1hr**	**2hr**	**6hr**	**12hr**	**24hr**
BU31	52 ***	39 ***	28 ***	14 ***	32 ***	13 ***	25 ***	21 ***	8 **
CW09[&]	-175 **	-75 *	-22	0	-14	0	-10	-14	0
QT10	-24 ×	-15	-4	6 *	0	0	-6	-7	0
VA01	13 ×	11 *	7 ×	7 **	11 **	5 *	0	283	0
VA04	12	4	3	3	-3	3	-8 ×	- 7	0
VA13	40 ***	26 ***	18 ***	9 ***	21 ***	6 **	17 ***	9 ×	3 *
VW14[&]	-229 *	-156 *	-122 **	-50 *	-78 *	-38 *	-64 ×	-57 ×	-31

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
& < 30 years of data available

Seasonal summaries are given below in Table 3.9. Positive, statistically significant increases in the spring months (April, May and June) indicate rainfall threshold exceedance frequency is rising during these months. Note, however, that statistical significance in Table 3.9 does not necessarily indicate the presence of a robust trend, as it does for ATEC and rainfall intensity trends due to the presence in some cases of several years with no exceedances. Further work should consider the use of trend analysis specifically for discrete variables in order to properly investigate trends in STEC (and possibly MTEC).

Table 3.9 STEC trends (# of occurrences per year)

a. Winter

			5 min		*15 min*		*1 hr*		*6 hr*
GVRD	BU31		0.00		0.00		0.00		0.00
	CW09[&]	*	-0.25	*	-0.25		0.00		0.00
	DN25		0.00		0.00		0.00		0.04
	QT10		-0.04		0.00		0.00	×	-0.04
	VA01		0.00		0.00	*	-0.04		0.00
	VA04		0.00		-0.03	*	-0.04	**	-0.06
	VA13		0.03	×	0.00		0.00		0.00
	VW14[&]		-0.36		0.00		0.00		-0.10

b. Spring

			5 min		*15 min*		*1 hr*		*6 hr*
GVRD	BU31	**	0.21		0.06	×	0.00		0.00
	CW09[&]		-0.31		-0.31		0.00		0.00
	DN25	**	0.21	*	0.09	***	0.12		0.00
	QT10		0.05	×	0.03	×	0.00	*	0.00
	VA01	*	0.05		0.00		0.00	*	0.03
	VA04	*	0.05		0.05		0.00		0.00
	VA13	***	0.14	***	0.06	***	0.05	×	0.00
	VW14[&]		-0.50		-0.25		-0.25	*	-0.14

c. Summer

			5 min		*15 min*		*1 hr*		*6 hr*
GVRD	BU31		0.00		0.00		0.00		0.00
	CW09[&]	*	-0.40	*	-0.40		-0.06		-0.06
	DN25		0.00		0.00		0.00		0.00
	QT10		-0.03		0.00		0.00		0.00
	VA01		0.03		0.03		0.00		0.00
	VA04		0.03		0.00		0.00		0.00
	VA13	*	0.07	×	0.02		0.00	*	0.00
	VW14[&]	*	-0.86	×	-0.25	×	-0.25		0.00

d. Fall

			5 min		*15 min*		*1 hr*		*6 hr*
GVRD	BU31		0.08	+	0.14	*	0.08	*	0.09
	CW09[&]	**	-0.80	**	-0.80		-0.13		-0.13
	DN25		0.08		0.00	+	0.11		0.00
	QT10	*	-0.17		-0.04		0.00		0.00
	VA01		0.03		0.00		0.00		0.03
	VA04		0.03		0.00		0.00		0.00
	VA13	*	0.12		0.02	*	0.08	**	0.10
	VW14[&]	*	-0.88	**	-0.50	**	-0.50		-0.33

*** Significant at 99.9%
** Significant at 99%
* Significant at 95%
× Significant at 90%
& < 30 years of data available

3.3 Cycles of Historical Climate Variability

Climate variability in BC is particularly influenced by two key factors: i) the El Niño Southern Oscillation (ENSO) and ii) the Pacific Decadal Oscillation (PDO). The effects of PDO and ENSO in Western North America are well documented (Fleming 2006, Wang *et al.* 2006, Stahl *et al.* 2006).

ENSO is a tropical Pacific phenomenon that influences weather around the world and across Canada. There is evidence that ENSO has occurred for millennia (Sandweiss *et al.* 1996) with cycles lasting 2 to 7 years and events persisting for 6 to 18 months. On average, warm "El Niño" events bring warmer temperatures and less precipitation to BC, while cool "La Niña" events bring cooler and wetter conditions.

The PDO is a pattern of mid-latitude climate variability with a much longer time scale than ENSO (~20-30 year cycles, Mantua *et al.* 1997). The most recent PDO shift occurred in 1976, resulting in a positive (warm) phase that dominated from 1977 to (at least) the mid-1990s (Hare and Mantua 2000). Chen *et al.* (1996) compared the winters from 1950-59 to those from 1985-90 and found a decreasing trend in precipitation north of 36°N.

There is a strong link between ENSO and PDO in that the phase of PDO amplifies or dampens effects of ENSO events (Gershonov and Barnett 1998, Hamlet and Lettenmaier 1999, Snover *et al.* 2003). Note also that the relative frequency and intensity of ENSO and PDO are changing in response to global climate change (Trenberth and Hurrell 1994, Timmermann 1999). In other words, ENSO and PDO may begin to impact local climate in a way that has not been observed thus far. Trenberth *et al.* (2005) discusses the changing character of precipitation that may occur as a result of climate change.

KWL-02 reports that the two most significant periods of threshold exceedances coincide with the two most intense El Niño events of the 20^{th} century for rainfall intensity durations up to 1 hour. Visual comparison of PDO and SOI (an ENSO index – see Section 2) to exceedance threshold time series (not shown) shows a subjective, weak coincidence of high exceedances with positive SOI (La Niña events) prior to 1976/77 and with positive PDO afterwards. Higher variability in the exceedances records also appears post-76/77. This interpretation lends support to the need for further (quantitative) investigation of this possible result. However, visual inspection of highly variable data is not suitable for determination of a cause and effect relationship, and results report in this manner must be treated with caution.

There is evidence that following the strong 1997/98 El Niño, a major transition in the North Pacific occurred (Rodionov *et al.* 2004). The PDO index switched signs to negative and remained so through the summer of 2002. During the winter of 2002/2003, however, the PDO index was positive (Peterson and Schwing 2003). Note, however that the annual PDO index can be misleading since the PDO tends to stay in each phase on a much longer time scale (~20-30 years) and short term anomalies in the index can occur within a phase. Thus, a consensus on whether we are now in a negative PDO has not been reached within the scientific community.

Some research suggests that conditions in the North Pacific may have moved out of oscillating between positive and negative PDO and infers that different spatial patterns in sea level pressure (SLP) and sea surface temperature (SST) are to be expected (Bond *et al.* 2003). For example, observations over four years (1999-2002) showed SLP and SST anomalies that did not resemble those before or after the shift of ~1976. This suggests that a new combination of these anomalies is persisting post-1998 that does not fit the original anomalies that were used to define positive and negative PDO (Bond *et al.* 2003, Minobe 2002).

Comparison of percent change difference in threshold exceedance between post- and pre-76/77 is used to investigate the effect of PDO (KWL-02). Results are shown in Table 3.10 and include data up to end of 2005. Further work might attempt to consider effects of possible changes to PDO in 1989 and 1998.

Results are consistent with a relationship between positive PDO phase and generally increased GVRD rainfall threshold exceedance, particularly at the 30-minute duration. This result is fairly coherent across the GVRD with the exception of QT10, which has large decreases in exceedances at longer durations in the positive PDO period (post-76/77). Note also that the strength of a relationship would be expected to be modest due to the large number of other factors that influence rainfall (Mote 2003).

Table 3.10 Change in exceedance (TSEC) from pre-76/77 to post-76/77 period over all durations at individual stations and averages over all periods.

Stations	5 min	10 min	15 min	30 min	1 hr	2 hr	6 hr	12 hr	24 hr	Mean*
BU31	76%	87%	86%	117%	86%	109%	79%	66%	99%	**89%**
DN25	39%	40%	48%	78%	38%	28%	9%	6%	19%	**34%**
QT10	-4%	3%	13%	65%	14%	26%	-20%	-20%	-22%	**6%**
VA01	37%	39%	47%	82%	42%	54%	-9%	-8%	-5%	**33%**
VA04	26%	23%	25%	35%	4%	14%	-6%	2%	32%	**17%**
VA13	55%	61%	58%	77%	61%	61%	45%	40%	52%	**57%**
Mean	**38%**	**42%**	**46%**	**76%**	**41%**	**49%**	**19%**	**15%**	**29%**	

*This column is the most analogous to KWL-02 Table 6-8.

The comparison above does not indicate whether or not the differences between the two cases are statistically significant. To do so, a t-test was conducted. Table 3.11 shows higher averages and standard deviations in the post-76/77 data for almost all cases (italicized in Table 3.11 below). This result supports the visual analysis in terms of a shift that occurred in the records and greater variance post-76/77. In Table 3.11, bold indicates that post-76/77 data are statistically significant from pre-76/77. All stations have at least one period that is significantly different from the pre-76/77 population.

Table 3.11 Average exceedance (TSEC) from pre-76/77 and post-76/77. Standard deviations are shown in brackets, italicized post-76/77 values are greater than their corresponding pre-76/77 values. Bold values indicate post-76/77 populations are significantly different from the pre-76/77 population. Results are shown for 5 time periods only.

Stations	*Period and Analysis*	*n*	*5 min*	*15 min*	*1 hr*	*6 hr*	*24 hr*
BU31	Pre-76	276	1.34	0.59	0.63	0.60	0.16
			(1.85)	(1.07)	(1.15)	(1.04)	(0.47)
	Post-76	177	***2.98***	***1.49***	***1.59***	***1.37***	***0.46***
			(3.68)	**(1.90)**	**(1.99)**	**(1.94)**	**(0.99)**
DN25	Pre-76	156	2.26	0.99	1.27	1.38	0.40
			(2.64)	(1.42)	(1.84)	(1.77)	(0.72)
	Post-76	324	***3.35***	***1.62***	***1.87***	*1.51*	*0.49*
			(4.41)	**(2.42)**	**(2.37)**	(1.82)	0.89)
QT10	Pre-76	216	2.85	0.95	0.97	1.13	0.30
			(3.41)	(1.43)	(1.55)	(1.71)	(0.71)
	Post-76	348	2.74	*1.09*	*1.11*	0.92	0.24
			(3.51)	(1.63)	(1.78)	(1.44)	(0.62)
VA01	Pre-76	216	1.18	0.51	0.58	0.69	0.20
			(1.61)	(0.88)	(1.01)	(1.14)	(0.49)
	Post-76	216	***1.71***	***0.82***	***0.88***	*0.75*	0.19
			(2.23)	**(1.28)**	**(1.43)**	(1.34)	(0.55)
VA04	Pre-76	180	1.51	0.78	0.95	0.87	0.23
			(1.90)	(1.27)	(1.40)	(1.33)	(0.55)
	Post-76	204	***1.97***	*1.00*	*0.99*	0.82	*0.32*
			(2.56)	(1.48)	(1.52)	(1.33)	(0.92)
VA13	Pre-76	288	1.42	0.68	0.69	0.71	0.19
			(2.11)	(1.23)	(1.36)	(1.17)	(0.53)
	Post-76	216	***2.50***	***1.23***	***1.30***	***1.12***	***0.32***
			(3.34)	**(1.71)**	**(2.06)**	**(1.50)**	**(0.74)**

The analysis above suggests that the pre-76/77 and post-76/77 records are different from each other at most durations. Furthermore, at shorter durations in particular, positive PDO is associated with increased exceedance and increased variability (as above; Table 3.10). In addition to comparing the means of two periods, it is instructive to consider the trend before and after the PDO shift.

Trend analysis was completed for 5-minute duration threshold exceedances (see Figure 3.3) and shows that trends were negative during pre-76/77 and positive at all stations but QT10 afterwards. Together, the results in this section suggest that a return to a negative PDO phase could reduce exceedances whereas the presence of a recent underlying trend towards increasing exceedances could also exist.

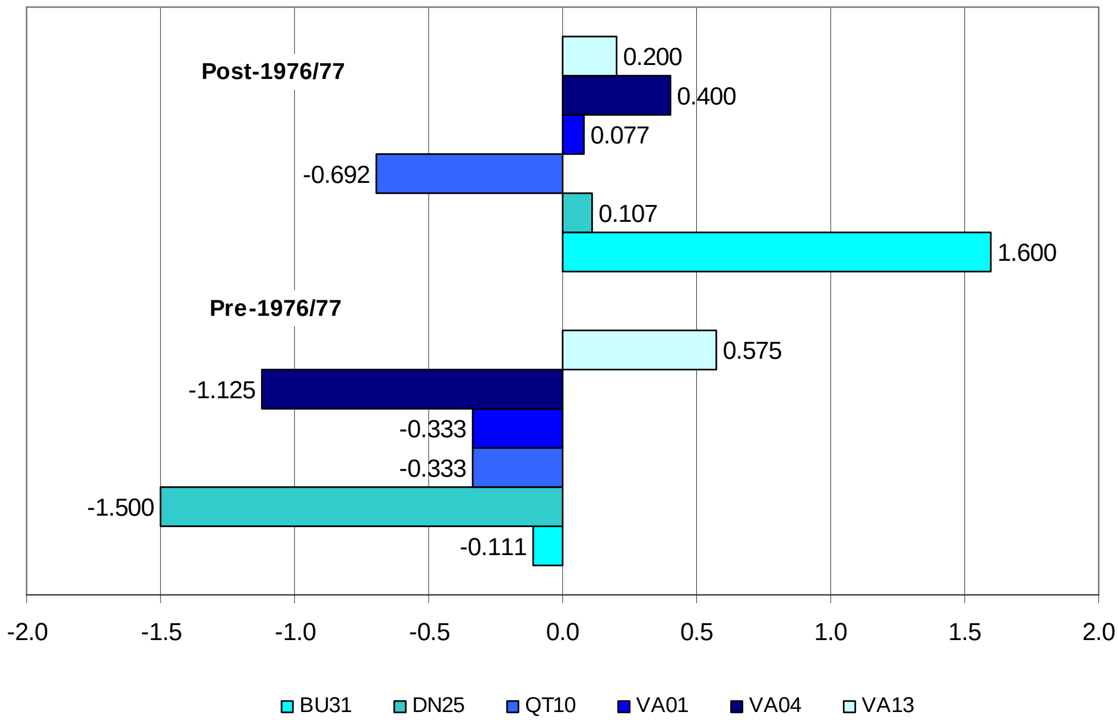


Figure 3.3 ATEC trends (occurrences per year) for the 5-minute duration, pre-76/77 and post-76/77.

A recently developed robust statistical methodology to determine effects of ENSO and PDO on temperature, precipitation, and streamflow (Fleming *et al.* 2007) indicates two results of importance to the analysis in section 3.3. First, the effects of ENSO and PDO on precipitation for the Georgia Basin are broadly consistent with those presented here. Secondly, however, effects of ENSO and PDO are not statistically significant from each other. In other words, the variability is larger than the signal: all El Niño years are on average drier than non-El Niño years but the variability is so large that many individual El Niño years deviate from this average.

3.4 Comparison of Results to Historical Total Precipitation

Despite limitations of short record lengths, rainfall intensity (section 3.1) and threshold exceedance (section 3.2) have generally been increasing in the GVRD: at some locations more than others, more for the shorter durations, and mostly in spring and winter. However, this analysis does not determine the degree to which these changes are due to underlying increases in annual precipitation itself or to systematic changes in how rainfall in the GVRD has been occurring (rainfall type and systematic changes to type of weather systems). It is thus important to compare results to trends in annual and seasonal precipitation, and to consider how changes to typical weather systems, i.e. *synoptic climatology*, may be related to these changes.

3.4.1 Historical Trends and Cycles in Total Precipitation

In addition to precipitation intensity and threshold exceedance, other aspects of precipitation have been studied because they are important to stormwater management and may affect other hydrologic variables such as soil moisture which can affect soil erosion (Palecki *et al.* 2005). Most studies indicate increases in total precipitation for Pacific North America, with magnitude depending on the period of record, type of data (annual or seasonal), and location (Zhang *et al.* 2000, Karl and Knight 1998, Groisman *et al.* 1994, Kunkel *et al.* 1999, Kharin and Zwiers 2000).

Recent research into spatial precipitation trends by Mote (2003) using adjusted datasets found a precipitation increase greater than 60% per century (1930-1995) for south central BC. Seasonally, precipitation trends in spring and early summer (April – July) increased the most (Mote 2003). South of 55°N, precipitation increased during the period of record (1910-2001), and there was a double-digit increase in the frequency of heavy and very heavy precipitation over this time period (Groisman *et al.* 2005).

Thus, future projections of total precipitation trends may also be indicative of future rainfall intensity and frequency of threshold exceedance, since trends in total precipitation trends are increasing during similar times of the year as trends in rainfall intensity and frequency of threshold exceedances. Total precipitation also exhibits similar patterns in response to the PDO and ENSO as intensity and exceedances (Gan *et al.* 2007). However, a trend toward decreasing storm total precipitation and storm duration in most seasons was found in the Western United States while storm intensity increased (Palecki *et al.* 2005).

3.4.2 Synoptic Types and Total Precipitation

Synoptic typing may be used to provide additional context for the underlying rainfall variability occurring in the GVRD. Stahl *et al.* (2006) analysed a set of thirteen synoptic patterns that describe the most common weather systems affecting BC. If this set is constant in time, as suggested by the very small change in frequency of occurrence between the 1961-1989 and 1948-2003 time periods (McKendry *et al.* 2006), then it may be worthwhile to investigate whether the trends in occurrence of synoptic types are consistent with changes in rainfall intensity and frequency.

For example, synoptic types (see Stahl *et al.* 2006) 7, 10, 12 and 13 occur more commonly during positive PDO phase while types 2 and 3 occur less commonly. The wettest synoptic types at YVR are (in order) 10, 3, 12, 4, 9, 6, and 13 (Stahl *et al.* 2006), although some of the patterns themselves are associated with wetter or drier conditions depending on the phase of ENSO and PDO in which they occur.

Thus, synoptic types 10 and 12 occur more often during positive PDO and are among the wettest types, but they do not occur in spring and summer. The modest increase in rainfall intensity (October through January) and exceedance trends found here could be attributable, in part, to an increase in the occurrence of these types. These changes in synoptic types are consistent with a tendency towards increased frontal systems (in winter) during the positive phase of the PDO and due to global warming.

Note that the preceding discussion assumes that intensity and exceedance are related to overall precipitation amount. Further analysis of the relationship between rainfall and synoptic type would be most valuable if frequency of synoptic types were compared with rainfall intensity and threshold exceedance results directly, rather than total precipitation.

3.4.3 Future Projections of Total Precipitation

Although trends towards increased occurrence of intense rainfall could be part of a body of evidence indicating a discernable human effect on the climate (Easterling *et al.* 2000), the analysis presented here is not directly applicable to climate change detection and attribution. However, 50%-85% of the 1925-1999 global (from 40°N to 70°N) pattern of precipitation trend has been attributed to the human influence on climate (Zhang *et al.* 2007).

A continued increase in annual precipitation at mid-latitudes is projected by Global Climate Models, or GCMs (Christensen *et al.* 2007, Trenberth 1999). Climate projections specifically for the GVRD were also compiled for this update. These projections are based on results from several GCMs following different global greenhouse gas emissions scenarios (IPCC Special Report on Emissions Scenarios, Table 3.12). The analysis was conducted for a regional average of several grid boxes centered on the GVRD. Figure 3.4 shows results from the Canadian Global Climate Model, where the GVRD region used includes three grid boxes.

Projections are also presented as "box and whisker plots" (Figure 3.5) that show the median value within the box, the upper 75th and the lower 25th percentile of the projections as the upper and lower boundaries of the box - thus the box represents the middle 50% of the range of projections. The full range of projections, or 1.5 standard deviations, whichever is less, are shown as the upper and lower 'whisker' marks at the end of the lines above and below the box. Each plot shows the projected difference over the 21st century from the historical baseline.

Table 3.12 Climate model and emissions scenarios used for boxplots

Model	**Abbreviation**	**Emissions scenarios (number of experiments)**
Canadian Global Climate Model version 2	cgcm2	A2 (3), B2 (3)
Geophysical Fluid Dynamics Laboratory R30	gfdlr30	A2 (1), B2 (1)
European Centre/Hamburg Model 4	echam4	A2 (1), B2 (1)
Commonwealth Scientific Industrial Research Organization Mk2b	csiromk2b	A1 (1), A2 (1), B1 (1), B2 (1)
Center for Climate Research - National Institute for Environmental Studies (Japan)	ccsrnies	A1FI (1), A1T (1), A1 (1), B1 (1), A2 (1), B2 (1)
Hadley Centre Coupled Model version 3	hadcm3	A2 (3), B2 (2), B1 (1), A1FI (1)
National Center for Atmospheric Research Parallel Climate Model	ncarpcm	A2 (1), B2 (1)

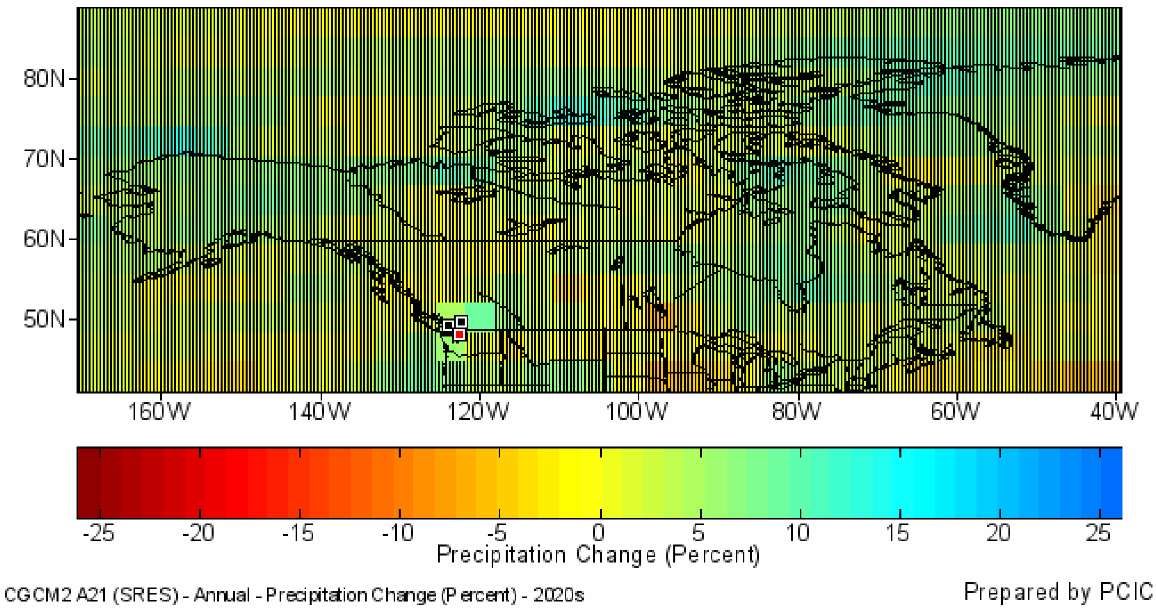


Figure 3.4 GVRD region (see black and red squares) and grid boxes selected from the Canadian Global Climate Model.

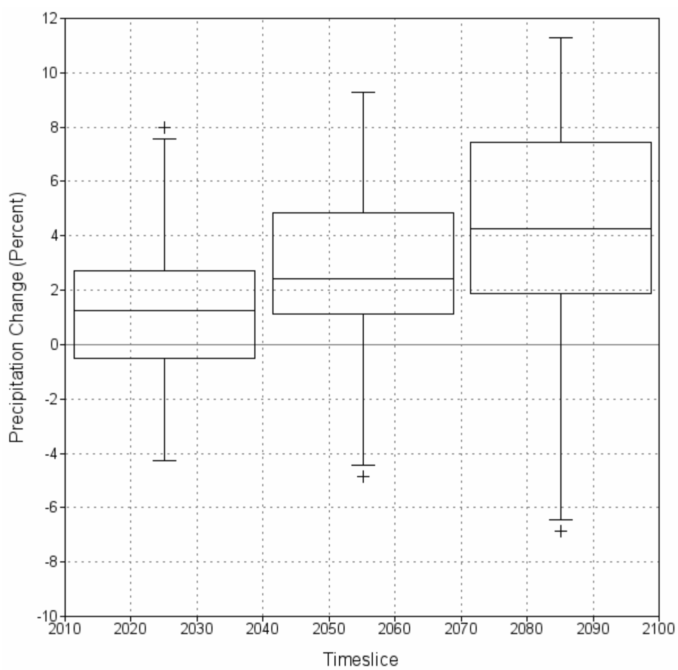


Figure 3.5 Box and whisker plot for the annual future precipitation projections for 2020s, 2050s and 2080s. See text for full explanation.

Individual model results, regional statistics, plots and additional seasonal output are also available online[7]. In addition, the geographical region under consideration may be modified.

[7] http://www.PacificClimate.org/scenarios/

The median precipitation projection is shown along with the 25th and 75th percentiles of results (Table 3.13). The annual and seasonal median projection results over the 21st century are as follows. For the 2020s, the annual, winter, spring and fall periods show a small increase. Summer precipitation is projected to decrease by 16%. This pattern of projected decreases in summer and increases in all other seasons continues through the 2050s and 2080s. Winter precipitation is anticipated to rise 6% by the 2020s, 9% by the 2050s and 12% by the 2080s.

This median projection would be broadly consistent with a continuation of precipitation increases that have been occurring in historical precipitation for Canada and North America (section 3.4.1). However, there is a great amount of variation in regional averages and in the probability of increasing extreme values in precipitation studies (Trenberth *et al.* 2005, Whilby *et al.* 2002).

Finally, the projections for the 2020s, 2050s, and 2080s shown in Figure 3.5 and Table 3.13 are each averaged over 30-year periods and expressed as the difference from the 1961-1990 baseline. Therefore, decadal variability is suppressed in these estimates. However, future precipitation in BC will continue to be strongly influenced by PDO cycles and ENSO events (section 3.3), with effects superimposed on the projections below. A switch to the negative phase of the PDO is possible and would tend to moderate patterns of increased rainfall intensity and threshold exceedance. It is possible that a continuation of PDO conditions of the past five years, the initiation of negative PDO, or even a return to positive PDO, could occur

Table 3.13 Precipitation projections (% anomaly from historical climatology) for 2020s, 2050s and 2080s for 25th percentile, median, and 75th percentile of emissions scenarios.

Projection	*Time Period*	*25th Percentile*	*Median*	*75th Percentile*
2020s				
	Annual	-1	1	3
	Winter	1	6	9
	Spring	0	2	7
	Summer	-19	-16	-5
	Fall	-3	0	3
2050s				
	Annual	1	2	5
	Winter	4	9	14
	Spring	-2	2	8
	Summer	-33	-25	-14
	Fall	0	2	6
2080s				
	Annual	2	4	7
	Winter	8	12	19
	Spring	-1	5	9
	Summer	-36	-28	-11
	Fall	1	4	9

4 Conclusions

This report provides an update to KWL-02 with additional data (to 2005). The update focuses mainly on observed trends in rainfall intensity and threshold exceedance, including a discussion of the influence of climate oscillations (ENSO and PDO). Results are compared to trends in total precipitation, and future projections of total precipitation from Global Climate Models are presented. Overall, findings that annual and seasonal trends in rainfall intensity and threshold exceedance frequency have increased during the 1950-2005 period generally reinforce conclusions from KWL-02. However, the trends do not occur uniformly across durations, seasons, or spatially. Thus, while an overall pattern of increasing rainfall is apparent, the short record lengths and gaps in records remain a considerable technical limitation.

Some of the highlights of the discussion and results (section 3) include:

Rainfall intensity:

- Positive, statistically significant weak trends were found on an annual basis at more than half of the stations
- There does not appear to be a consistent relationship between presence or magnitude of trends and elevation or spatial distribution
- Most of the statistically significant positive trends occur within the 5min to 2hr durations
- Relatively strong (>10mm/hr per century) statistically significant increases in monthly trends are occurring during April, May and June within the shortest durations (particularly 5 and 15 minutes)
- June has the strongest trend in rainfall intensity, in the 5-minute duration
- May and June have the highest total number of significant (>95%) monthly rainfall trends from all stations
- March, April, and October through January also have several significant (>95%) seasonal rainfall trends

Threshold exceedance:

- Some positive trends are found in the annual records at most stations
- Positive seasonal trends are strongest for the spring (Apr-May-June) months
- Positive annual and monthly trends occur mainly in the short durations (up to 2 hours)

Climate Variability:

- Trends in rainfall intensity and threshold exceedance include the combined effects of natural variability, including influence of ENSO and PDO, as well as climate change
- Impacts of ENSO and PDO themselves may be affected by climate change
- Rainfall exceedance prior to 1976/77 is statistically distinct from the post-76/77 record which suggests an influence of PDO on rainfall exceedance, although the presence of underlying trends towards increased exceedance complicates this interpretation

- Although the status of PDO remains uncertain, trends have continued to increase at several stations, and there is some evidence that the observed shifts in PDO of the last century may not continue in the same way in future

Climate Change:

- Decreased summer precipitation is projected over the next century
- Increased precipitation is projected in all other seasons, particularly winter over the next century
- A slight net annual increase in precipitation is projected over the next century
- Patterns of increased rainfall intensity and threshold exceedance are consistent with a tendency towards increased frontal systems (winter and spring) and convection (spring) during the positive phase of the Pacific Decadal Oscillation and due to global warming.

Note that the records used in this study are of various lengths and contain numerous data gaps, which create difficulties when attempting to interpret results. Stations with different record lengths, or data gaps cannot be readily compared. Changes in gauge location or environmental effects, such as the installation of the cooling tower at DN25, also create difficulty when attempting to resolve or understand long-term changes (Groisman and Easterling 1993). Thus, the application of methods such as data infilling, or the use of adjusted climate records may be one means of improving estimates of trends in precipitation intensity and frequency. These methods and other recommendations for further analysis are discussed in Appendix A.

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Appendix A: Recommendations for further analysis

Data quality and local station limitations

1. Missing values:

Several stations have multiple years of missing data. This presents a challenge when comparing the results from stations within the network to each other and when attempting to look for regional trends. Regional averaging (below) would reduce the impact of missing values and stations could be compared to each other using only common years. Data gaps could also be in-filled. For example, AQUARIUS Time-Series™ software can use data from nearby MSC stations to in-fill missing records. Probability density functions (PDFs) can be applied to define relationships between the 24-hour period and shorter duration records and then these relationships can be used to in-fill shorter durations.

2. Use of recently digitized data:

Continuing to decrease the length of missing periods of data by digitizing records is far preferred to filling missing values. New updates should continue to take advantage of additional observations that occur as well as additional historical data as it becomes digitized (such as daily rainfall at the three MSC stations for 2001-2005 which was not used during preparation of the report but is now available).

3. Data evaluation:

The GVRD could undertake a review of the gauges used to collect data in order to evaluate their relative strengths and weaknesses in terms of inclusion in the study, or expansion of the network used (see 4 below). For example, are the gauges heated tipping buckets and if so, what is their accuracy? If they are not winterized it is possible that there is gauge under-catch during winter which would affect some of the storm precipitation characteristics (Groisman and Legates 1994).

Preprocessing may also be an important consideration for future analysis of GVRD rainfall. Groisman *et al.* (2005) discusses preprocessing of daily precipitation data for Canada to restore the homogeneity of the time series before trends in intensity were tested. Groisman *et al.* (2005) suggests that preprocessing is necessary because the original data was affected by changes in observational practices and instruments. Additionally, alternate research has outlined techniques for removing the artifacts of preprocessing (Groisman and Rankova 2001; Groisman *et al.* 1999; Groisman 2002).

The Adjusted Historical Canadian Climate Data (AHCCD) provides rehabilitated precipitation and homogenized temperature data sets for Canada, which can be used for climate research. These data incorporate a number of statistical adjustments to the original station data. The AHCCD station data could be utilized by generating a double mass curve of a GVRD station to a nearby AHCCD station to reveal inconsistencies in measuring techniques at the GVRD stations. Adjusting the data would give greater confidence in the trends and would also make the results more directly comparable to those from other studies.

4. Spatial analysis:

Station (point) examination of precipitation events, such as undertaken in this report, can generate an understanding of rainfall at that specific location. Owing to the highly variable nature of rainfall (Dai 2001), point analysis can sometimes be misleading or less valuable than spatially broad analyses.

Mote (2003) examined regional averages that include the GVRD. Inclusion of stations from outside of the region will improve the relative strength of climate variability and trends as compared to local effects. The importance of examining rainfall patterns over an appropriately area allows for consideration of a large number of stations while smoothing out effects of localized topography and other non-climatic factors in favour of a more regionally coherent climate record (Mote 2003).

In addition to simply regionally averaging the results, gridded data could be used. Blending station and gridded data as well as interpolating point observations onto a grid is becoming increasingly important for comparing observational data with climate model simulations (Hegerl *et al.* 2006). Finally, a comparison of trend results at individual stations to regional synoptic types (Stahl *et al.* 2006) should be conducted in order to make a connection between trends and underlying changes in meteorological conditions.

5. Length of record:

Analysis over a larger region will allow not only a higher number of stations in the later part of the record, but also extension of analysis into earlier parts of the record. The inclusion of the earlier part of the 20th century would allow for better estimation of variability as additional cycles of ENSO and PDO could then be analysed. Additionally, trend analysis would be improved as longer records may provide more statistically robust estimates. One possibility for extending the period of analysis includes using data from GVWD watersheds, which can extend back as far as 1914. Investigation of the effect of start date on trends also allows for a better understanding of regional climate variability.

Methods: broadening analysis beyond rainfall intensity and exceedance

6. Additional parameters:

Consideration of rainfall trends in the GVRD in isolation of temperature and snowfall leaves a major gap for interpretation of results. If increases in rainfall are occurring in winter and spring, it is not clear how much is due to an overall increase in precipitation, and how much is due to increase in temperature.

7. Hydrological and regional climate modeling:

Distributed hydrological models, Energy-Moisture balance hydrological models such as the Variable Infiltration Capacity Model used at the University of Washington, and Regional Climate Models such as the CRCM operated by Ouranos may be used to diagnose results at high spatial and temporal resolution, with the added advantage that other relevant aspects of the hydrological cycle (such as streamflow) may also be available. In the absence of regional modeling, the GCM projections should be updated using AR4 projections.

8. Literature review:
To date, much of the analysis has been performed in order to make the most of the data available while keeping analysis simple enough to interpret results. In the time since KWL-02, several other studies have used alternate statistical methods, which may yield richer results for investigation of trends as well as variability.

9. Seasonal climate predictions:
KWL-02 suggested that low skill for seasonal climate predictions of rainfall intensity and exceedance based on multiple linear regression analysis. However, experimental predictions of streamflow, such as those produced at the University of Washington[8], may yield a useful level of skill.

10. Event-based enquiry:
Cumulative effects of storm segments are important as they work in combination on the natural and human environments to create runoff, soil erosion, and flooding. Palecki *et al.* (2005) analysed annual and seasonal trends in mean storm characteristics such as total storm precipitation, storm duration, storm intensity, and 15-minute maximum intensity using a linear regression and a Student's t-test of the slope to determine the significance of the trend in the United States. All of these components contribute to the impact of a given storm.

An accurate evaluation of the threat of changes in precipitation should reflect not only these but also antecedent moisture conditions and snow pack leading up to the event. Defining storm characteristics leading to events such as seasonal water availability from the source regions, atmospheric water vapor capacity, and the storm precipitation mechanism helps to predict high impact events (Palecki *et al.* 2005). The seasonality, frequency, severity and geographic extent of an event or events of similar magnitudes can be considered (i.e. aggregate all events to form a sample over a given threshold, apply cluster analysis and use extreme probability statistics). Examining trends and their relationship to climate change may help the GVRD to plan and mitigate for such occurrences.

11. Probability density functions (PDFs):
PDFs are used for hydrologic and erosion modeling and are formed by fitting analytical curves to empirical storm characteristic probabilities (Palecki *et al.* 2005). *L*-moments software can be used by the GVRD to examine the 100-yr return interval estimates for each variable and season to examine extremes for each station by fitting the two-parameter Gumbel distribution to the annual extreme series using (Hosking 1991).

12. Seasonal trends:
The Mann-Kendall (MK) test is one of the most widely applied statistical tests for trends in climate time series (Mann 1945). A modified version of the MK test was proposed by

[8] http://www.cses.washington.edu/cig/res/hwr/muniwaterfc.shtml

Hirsch *et al.* (1982). This version is more appropriate for seasonal data, and is referred to as the Seasonal MK test. In this version trends in seasons with small values are not dominated by larger values in other seasons (Lettenmaier *et al.* 1994) and serial dependence, such as correlation between months, is accounted for by inflating the variance of the test statistic (Hirsch and Slack 1984). A version of Mann-Kendall that includes seasonal Mann-Kendall tests is available for download online[9]. This could be applied by the GVRD to test for seasonal trends in rainfall intensity.

13. Choice of seasons:
The more common breakdown into seasons of DJF, MAM, JJA, SON rather than JFM, AMJ, JAS, OND for winter, spring, summer and spring respectively (where DJF equals December-January-February and so on) would facilitate comparison to other studies. In addition, for computations of wet seasons, months from consecutive water years would yield more robust results than JFMOND by calendar year.

14. Selection of thresholds:
Instead of defining rainfall exceedance thresholds based on millimeters of rain, event frequency thresholds could be based on percentiles. This would make trends comparable to other studies and would allow for relevant comparison of trends from one station to another.

Groisman *et al.* (2005) defined a daily precipitation event as heavy when it fell into the upper 10% and/or 5% of all precipitation events; as very heavy when it fell into the upper 1% and/or 0.3% of precipitation events; and extreme when it falls into the upper 0.1% of all precipitation events. These percentiles can be equated to return periods (at each station individually). The 0.3% return period corresponds roughly to one daily event in 3 to 5 years for annual precipitation and approximately 10 to 20 years for seasonal precipitation, depending on the probability of daily rain events for a given location.

15. Further analysis of climate variability:
The preliminary comparison of rainfall during pre- and post-76/77 PDO phase shift may be expanded upon by considering longer-term records at a smaller number of stations, and by considering a possible phase shift in 1989 or 1998. In addition to PDO, the user of longer-term records would allow for investigation of effect of state of ENSO or other teleconnection patterns as well as in Gan *et al.* (2007).

[9] http://www.mai.liu.se/~cllib/welcome/PMKtest.html

Appendix B: Rainfall catalogue, station records and notes

Table B1: Summary of GVRD stations, available data and updated data (2001 - 2005)

STN ID	Start date	End Date	1949	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73
VA **1**	Mar-57	Present									D<																
VA **4**	May-58	Present										D<															
CW **9**	1947*	Present											P<	P<	P<	P<	P<	P<	P<	P<	P<	P<	P<	P<	P<	P<	P<
QT **10**	Jan-59	Present																									
VA **13**	Jul-49	Present																									
VW **14**	1959	Present											D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<
DN **15**	Mar-64	Present																P<	P<	P<	P<	P<	P<	P<	P<	P<	
DN **25**	Jul-64	Present																D<									
BU **31**	Sep-50	Present		D<														D<									

STN ID	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	2000	01	02	03	04	05
VA **1**			D<	D<	D<	D<	D<	D<	D<	D<	D<			D<															N	N	N	N
VA **4**	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<	D<								D<		D<		D<	D<		N	N	N	N
CW **9**	P<	P<	P<									D<				D<	D<					D<							N	N	N	N
QT **10**																									D<				N	N	N	N
VA **13**	D<	D<	D<	D<	D<	D<			D<							D<			D<				D<	D<		D<	D<		N	N	N	N
VW **14**	D<	D<	D<	D<	D<	D<			D<	D<	D<	D<	D<	D<	D<	D<	D<	D<			D<								N	N	N	N
DN **15**	P<	P<	P<	P<	P<	P<													D<		D<						D<		N	N	N	N
DN **25**																	D<	D<	D<	D<									N	N	N*	N*
BU **31**																	D<									D<			N<	N	N	N

Where years start previous to 1950, this data is not used for analysis

Legend

- (grey) Data continuous and complete in record
- D< Daily totals and Peak Intensities but only partial for year (some months missing)
- P< Peak Intensities but only partial for year (some months missing)
- N New Data updated in this assessment, all stations stopped recorded 10min durations in August 2005
- (black) No data available
- N< New but some months missing
- N* Rain gauge relocated

Table B2: Rainfall intensity and frequency: stations, record availability, durations and notes regarding any missing data or information

GVRD Stations

Stations	***Record Availability***	***Rainfall Intensities***	***Rainfall Threshold Exceedance***	***Notes***
BU31: Confederation Park	1950-1973†	NA: Jan-50 to Aug-50, Oct-64	NA: 1950	Oct-64 cont. 0's for exceedance
	1988-1997†	NA: Apr-90, Jun-99 to Dec-99	NA: 1999	Apr-90 cont. 0's for exceedance
	2002 – 2005*	Complete*; NA: Jan-02 to Apr-02	NA: Jan-02 to Apr-02	In August 2005, collection of 10-minute rainfall intensity ceased.
CW09 Westburnco Reservoir	1959-1976†*	NA: Daily totals, 10 minute durations and sporadic months; totals, 5, 15, 30, 1hr, 2hr, 6hr, 12hr and 24 hrs updated	No exceedance available	
	1980 - 2001†	NA: Jul-85, Feb-89, Sep-89, Jan-90 to Mar-90, Jul-95	Complete*	ul-85, Feb-89, Sep-89, Jan-90 to Mar-90, Jul-95 cont. 0's for exceedance
	2002 - 2005*	Total, 5, 10, 15, 30 minute, 1, 2, 6, 12 and 24 hours updated	Complete*	In August 2005, collection of 10-minute rainfall intensity ceased.
DN25: Dist. N. Van. Municipal Hall	1964 - 2001†	NA: Jan-64 to Jun-64, Jul-90 to Jun-91, Apr-92, Oct-93 to Dec-93	NA: 1990, 1991	Jan-64 to Jun-64 is available for exceedance.
	2002 – 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.

DN15/82: Cleveland Dam	1964-1983†	NA: Jan-64 to Feb-64, Daily totals, 10 minute durations and sporadic months, 1973	No exceedance available	
	1992-2001†	NA: Oct-93 to Jan-94, Feb-00 to Mar-00	No exceedance available	
	Mar-64 to Dec-72*	5, 15, 30, 1hr, 2hr, 6hr, 12hr and 24 hrs additional data updated	No exceedance available	
	1974 – 1979*	5, 15, 30, 1hr, 2hr, 6hr, 12hr and 24 hrs additional data updated	No exceedance available	10 minutes and totals were not updated
	2002 – 2005*	Complete*	Complete*	Nov-04 station switched from DN15 to DN82 (Appendix C). In August 2005, calculation of 10-minute rainfall intensity ceased.
QT10: Coquitlam City Hall	1959-2001†	NA: Aug-98 to Oct-98	Complete*	Aug-98 to Oct-98 cont. 0's for exceedance
	2002 - 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.
VA01 Kitsilano High School	1958-1975†	NA: Jan-57 to Feb-57	Complete*	
	1976-1984†	NA: 10 minute durations and sporadic months; 5, 15, 30, 1hr, 2hr, 6hr, 12hr and 24 hrs updated	NA: 1976 to 1984	
	1987-2001†	NA: Jan-87 to Feb-87	NA: 1987.	
	2002 - 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.

VA04 Renfrew Elementary	1958-1973†	NA: Jan-58 to Apr-58	NA: 1958	
	1974 - 1987*	NA: Some totals, 10 minute durations and sporadic months	No exceedance available	
	1988 - 2001	NA: Oct-95, Mar-97 to Jun-97, Jun-99 to Feb-00	NA: 1999	
	2002 - 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.
VA13 Stanley Park Yard	1950-1974†	Complete*	Complete*	
	1974 – 1982*	NA: 10 minute durations and sporadic months, 1980, 1981; 6hr, 12hr and 24 hrs updated	No exceedance available	
	1988-2001†	NA: Oct-89, Jan-92 to Jun-92, Feb-96 to Mar-96, Jul-97, Aug-99 to Sep-99, Jul-00	Complete*	
	2002 - 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.
VW14 West Van. Municipal Hall	1959-1990*	NA: 10 minute durations and sporadic months ; 6hr, 12hr and 24 hrs updated, 1980, 1981	No exceedance available	
	1991-2001†	NA: Jul-91, Jan-94	Complete*	
	2002 - 2005*	Complete*	Complete*	In August 2005, calculation of 10-minute rainfall intensity ceased.

MSC Stations

MSC Pitt Polder	1960-1964	NA: Intensities	No exceedance available
	1965-1999†	NA: 24 hr, Mar-75 to May-75 durations, Oct-79, Aug-91 to Jul-92, Jun-96 to Sep-96, Dec-96, Mar-99 to Jun-99, Sep-99 to Dec-99	No exceedance available
	2000-2005†*	NA: Intensities, Oct -04	No exceedance available
MSC Surrey - Kwantlen	1960-1997†	NA: 24 hr, Jan-60 total, Mar-73 to May-73, Aug-80, Dec-80, Feb 81 total, Jan-89, Aug-89, Dec-89 to Mar-90, Jul-90, Feb-91 to May-91, Mar-92, Jun-96, Jul-96, Sept-96, April-Dec97	No exceedance available
	1998-2005†*	NA: all durations, Sept-98 to May-99, 2001, Oct-04 to Jan-05	No exceedance available
MSC YVR Vancouver Int'l Airport	1960-1999†	NA: Jan-60 to Mar-60, Jul-60 5 min, Mar-75 to May-75, Jan-76 to Mar-76 6 hr, Feb-78, Jul-84, Aug-92, Apr-99 to May-99, Aug-99 to Dec-99	No exceedance available
	2000-2001†	NA: all durations, Nov-00 to Dec-01	No exceedance available

† KWL-02 report

*Completed this update for 2001 - 2005: includes total, 5, 10, 15, 30 minute, 1, 2, 6, 12 and 24 hours updated for rainfall intensity, exceedance counts include 5, 10, 15, 30 minute, 1, 2, 6, 12 and 24 hours (August 2005 onward for 10 minutes is not available)

Appendix C: Data limitations

Several limitations to rainfall records were determined from the outset of the project. These were noted, and in some cases required that data not be processed owing to a lack of complete information. These cases are listed in Appendix B.

GVRD Stations

BU31: This station was decommissioned in 1999 and replaced with station BU80. The new station location is located approximately 1km away from the old station. There was no overlap of data collection during the time that BU31 was decommissioned and BU80 was set up. Due to known differences between proximal sites in rainfall there is a concern that shifts in location of this rainfall gauge may significantly alter rainfall collection. The data has been processed but requires further analysis and examination before it can be determined if significant shifts have occurred since the installation of BU80, and whether this is impacting the trend statistics.

DN15: This station was used in the KWL-02 report as a comparison for DN25 (see original report for a detailed information regarding this comparison). DN15 was decommissioned in 2004 and replaced by DN82. The new station is located proximal to its old location and therefore only very minor shifts are anticipated, which are not expected to significantly impact the rainfall records.

MSC Stations

As MSC rainfall intensity data was only available up to 1999 during preparation of the update, daily totals were used for 2000-2005, where possible. The MSC rainfall intensity data should be incorporated into the next update as soon as it becomes available.