Greater
Vancouver
Regional
District

Development of GVRD Precipitation Scenarios

Final Report
October 2002

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EXECUTIVE SUMMARY

The United Nations Intergovernmental Panel on Climate Change (IPCC) and the US National Academy of Science have concluded that the global atmospheric warming over the past 50 years can be attributed to greenhouse gas emissions. Atmospheric warming affects other parts of the climate system including precipitation which is the focus of this report. Specifically, this study aims to investigate the pattern of precipitation intensity in the Greater Vancouver Regional District (GVRD). This information is sought for management of existing sewerage and drainage infrastructure.

Precipitation measurement and analysis are problematic due to the intermittent nature of precipitation, short historic records, and errors such as those due to wind effects around the instrument. Given the latter, long- term precipitation trends in urbanised settings may reflect changes in urban roughness as cities grow. The effect of such changes in the wind environment of cities on precipitation measurements is unknown. Data used in this study are uncorrected for wind and evaporation effects. Furthermore, instruments used in the GVRD network are exposed in a non-standard fashion (e.g. on building roofs where wind effects potentially introduce further errors). However, despite these data limitations strong trends in the data record should still be identifiable.

In southwestern British Columbia, year to year precipitation variability is modulated by the Pacific Decadal Oscillation (PDO) (50-60 years cycle), and the El Niño-Southern Oscillation (ENSO). The magnitude of variability of these cycles is significantly greater than the accumulated changes currently attributed to the enhanced greenhouse effect. Consequently, trend analysis of the short historic record from the GVRD is fraught with difficulty. There is evidence that the last PDO warm phase that started around 1977 ended in 1998 or 1999 and that a cool phase has begun. Should this be confirmed in coming years, the effects on rainfall intensity of a PDO reversal may become obvious.

Data on precipitation intensity from 5 minutes to 24 hours durations for nine GVRD stations and three MSC stations were gathered. A month-by-month analysis for all station(s) demonstrates statistically significant upward trends particularly for the months of April, May and June, which are also the months of high convective activity. Clearest trends were found for the shorter durations (up to 2 hours). The authors caution that the period of record is too short to draw conclusions about long term trends in short duration precipitation and that “extrapolation” of these precipitation trends is not scientifically supportable.

High-intensity rainfall threshold exceedances were computed for all stations and durations. This analysis demonstrates an increasing trend in threshold exceedances particularly during the 1990s. An increase in threshold exceedances is noticeable between the last PDO cool phase that ended in 1977, and the last warm phase that ended probably in 1998.

PDO phases were found to also have a strong effect on snowwater equivalent of the North Shore Mountains as measured on Grouse Mountain. Winters during a PDO warm phase have significantly lower snowwater equivalents than winters during a PDO cold phase, although the year-to-year variations are strongly modulated by other effects such as ENSOs. A shift towards a PDO cool phase could mean higher-than-average water availability for the GVRD's reservoirs in the next two decades.

The results of this study are consistent with the findings from recent scientific literature suggesting that there is, as yet, little historical evidence for a sustained and significant increase in high intensity precipitation over southwestern British Columbia. Instead, this study identifies trends that are (a) weak (b) inconsistent both across the GVRD and over time (c) most significant in spring and summer months when total precipitation inputs are smallest and (d) seemingly modulated by PDO/ENSO cycles. These results are entirely consistent with previous observational and modelling studies and suggest that there is no urgent need to upgrade the capacity of the storm sewers, combined sewers, and drainage systems. Sanitary sewers will not be affected by changes in rainfall intensity. However, given that General Circulation Models indicate modest increases in total precipitation over the next century in this region, it would be prudent to upgrade existing storm and combined sewers and drainage systems to higher capacities as part of the regular maintenance cycle.

Climate change and resultant changes in precipitation is unlikely to be steady, year by year. There will be irregular cycles, many of which cannot be foreseen. Regular updates of this study are recommended to detect any sudden changes in rainfall intensities.

Section 1

Introduction

1. INTRODUCTION

1.1 BACKGROUND

Observations made by the City of Vancouver's Sewer Design Branch indicate that the overall annual number of high intensity rainfall days has increased since the mid-1970s at Vancouver Airport. This observation is consistent with internal GVRD examination of rainfall data at several of its rain gauges, as well as research by Catherine Denault at the Department of Civil Engineering at UBC, which showed a significant increase in precipitation intensities for durations up to 2 hours at the District of North Vancouver Municipal Hall raingauge (Denault, 2001, Denault et al., 2002).

There are a number of reasons that could explain observed trends, which include:

- changes to the monitoring equipment and/or monitoring protocol;
- natural climatic oscillations;
- the effect of urbanization; and
- global climatic change.

Should it be shown that the observed positive trends in precipitation intensities will persist in the future, water-related infrastructure will likely be affected. Changes in precipitation intensity and recurrence would primarily impact sewerage and drainage infrastructure.

Sewerage and drainage infrastructure systems are typically designed for quasi-stationary climatic conditions and do not take into account any long-term changes in precipitation and runoff pattern. If precipitation intensities increase over the next decades, it can be expected that some current sewer and drainage systems could lack sufficient capacity to provide the current level of flood protection and drainage by the second or third decade of the 21st century. As the life span of storm sewers, combined sewers and drainage systems is from 50 to 100 years, upgrade of the system may become necessary. In this report, sewerage is used synonymously with storm sewers and combined sewers and does not include sanitary sewers which are not affected by changes in rainfall.

This study, therefore, aims to reduce uncertainties in projecting future precipitation intensities in the GVRD to allow a scientifically based decision making on whether sewerage and drainage system upgrades will be necessary in the future.

1.2 WORK PROGRAM

DEFINITION OF STUDY AREA

The study area comprises the Greater Vancouver Regional District as shown on Figure 1-1. A number of other areas within the Lower Fraser Valley and southwestern British Columbia were added for completeness and comparison with GVRD data.

OBJECTIVES

The Work Program for this study was developed on the basis of the following objectives:

- collect relevant precipitation intensity data;
- review studies on changes in precipitation in western North America;
- perform a precipitation trend analysis;
- attempt to correlate Pacific climate oscillations to observed precipitation pattern; and
- attempt to assess observed precipitation trends.

With this information available, the GVRD can consider a follow-up study that aims to produce precipitation scenarios for the 21st century.

WORK PROGRAM

The scientific Work Program for this study is summarized in Table 1-1.

Table 1-1
Scientific Work Program

Major Activity	Work Tasks
1. Project Initiation	▪ Meet with clients to refine scope of work ▪ Co-ordinate data transferral to KWL ▪ Agree on schedule and timing of deliverables ▪ Obtain background information (reports)
2. Data Collection	▪ Collect data from GVRD and MSC stations on rainfall intensities ▪ Collect published data on PDO and ENSO ▪ Collect stream flow data ▪ Collect proxy data (dendroclimatology)
3. Literature Review	▪ Review relevant literature on climate change and variability in coastal North America and southwestern B.C. ▪ Review climate modelling via GCMs
4. Precipitation Trend Analysis	▪ Analyse monthly and annual data in precipitation intensities for stations in the GVRD ▪ Analyse annual data on rainfall amounts, temperature, snow, and streamflow in the GVRD and southwestern B.C.

Major Activity	Work Tasks
5. Trend Explanation	▪ Correlate observed variability with ENSO and PDO ▪ Quantify correlations where appropriate
6. Trend Extrapolation	▪ Attempt projection of observed trends using climatic driving forces ▪ Describe uncertainties involved in trend projection
7. Draft Report	▪ Prepare draft report ▪ Include maps, drawings, and documentation of work tasks
8. Draft Report Review	▪ Obtain in-house review of draft report ▪ Obtain peer review of draft report ▪ Obtain GVRD review of draft report
9. Trend Analysis II	▪ Rain intensity analysis based on intensity threshold exceedence
10. Presentation at GVRD	▪ Present findings at a seminar at the GVRD ▪ Obtain comments
11. Final Draft	▪ Prepare final draft report ▪ Include maps, drawings, and documentation of work tasks
12. Report Review	▪ Obtain in-house review of final draft report ▪ Obtain peer review of final draft report ▪ Obtain GVRD review of final draft report ▪ Finalize final draft report

PURPOSE OF REPORT

This report provides a comprehensive analysis of precipitation intensities in the GVRD including some related hydroclimatic variables such as streamflow and snow water equivalent. A large number of studies relating to the climate of coastal western North America were added to the study scope. This provides a basis for a decision by the GVRD on whether to proceed with a follow-up study that focuses on precipitation scenarios for the 21st century. This follow-up study would largely be based on the findings of this study as well as global circulation modelling.

Although this report focuses on changes in rainfall intensity over the past 40 years, it also addresses changes in rainfall amounts, temperature, snowfall, and streamflow.

REPORT FORMAT

This report includes four appendices. The first appendix is a detailed literature review of previous studies on climate and climatic variability in coastal western North America, and specifically southwestern British Columbia. The second appendix is a collection of graphs showing precipitation intensity data for all 11 weather stations analyzed. Appendix C includes this report and all relevant data and figures on a CD ROM which provides the GVRD with a convenient source of data for possible re-analysis as more data become available in the future. Appendix D is a detailed account of data quality. Appendix E is an index of technical terms used in this study.

Inclusion of most of the detailed technical content in the appendices allows the main report body to focus more closely on the analysis of precipitation intensity time series.

1.3 PROJECT TEAM

The project team consists of three collaborating groups. Matthias Jakob, Ph.D., P.Geo. of KWL acted as project manager and oversaw the collection and analysis of precipitation, temperature and streamflow data as well as proxy data. He also wrote the majority of this report. Christine Norquist, Hamish Weatherly, M.Sc., P.Geo., Anne Munro, Susan Jensen, and Karl Mueller of KWL collected, entered, and prepared climate data from the GVRD and Meteorological Service of Canada (MSC).

Dr. Ian McKendry, Associate Professor at the Geography Department at the University of British Columbia (UBC) and Rick Lee, M.Sc. of the Canadian Institute for Climate Studies (CICS) in Victoria wrote the Literature Review and provided input to all other aspects of this study. Rick Lee also provided precipitation and temperature data from southwestern British Columbia.

Chris Johnson, P.Eng. of KWL reviewed this study.

At the GVRD, Robert Hicks, M.Eng., P.Eng. and Arash Masbough, M.A.Sc., EIT acted as project managers and client review. Steve Morash assembled data and was responsible for data transfer to KWL. Ed von Euw of the GVRD provided useful comments to the draft.

In addition, Environment Canada contributed data to the study and participated in reviews of the report drafts.

Section 2

Background on Precipitation Processes

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2. BACKGROUND ON PRECIPITATION PROCESSES

The amount, intensity and duration of precipitation delivered to the Greater Vancouver Regional District is a complex function of processes operating at a variety of temporal and spatial scales. The objective of this review is to give a sense of the various factors that contribute to the precipitation "climate" of our locality. Major controls may be summarized as large scale, regional and local scale, and micro-scale. This section provides a brief summary of the complex range of processes that are fundamental to an understanding of the spatial and temporal variations in precipitation. Location specifics are then provided in Section 3.

2.1 LARGE SCALE PROCESSES

In the mid-latitude **troposphere**, the meandering west to east flow (including the **jet streams**) influences the intensity, lifecycle and tracks of cyclonic systems. Individual cyclonic storms tend to be "steered" by these upper tropospheric winds. During winter, when the temperature gradient between the poles and tropics is most strongly developed, these mid-latitude westerlies are strongest and spawn a succession of cyclonic storms that dominate the winter climate of southwestern British Columbia. The position, amplitude and length of these upper level wave-like features are also influenced on a seasonal basis through an atmospheric linkage initiated by the distribution of sea surface temperatures (SSTs). The distribution of SSTs varies on a variety of time and space scales, one the most dramatic of which is the **El Niño - Southern Oscillation (ENSO)** phenomenon in the equatorial region of the Pacific basin. Temperatures of the atmosphere and ocean influence the amount of water vapour in the atmosphere (i.e. precipitable water). All these observations illustrate that the atmosphere and ocean are strongly coupled.

Large-scale processes are most important in influencing cool season precipitation in B.C. when cyclonic storms (and their associated fronts) tend to produce long-duration precipitation of moderate intensities (hours to days). Most of the precipitation in the GVRD originates from this cyclonic origin and occurs during winter. **Convective precipitation** on the other hand is primarily driven by the development of an unstable atmosphere (relatively warm near the surface with relatively colder air aloft) and tends to occur in spring and summer. Often highest intensities of precipitation occur during convective events. While this broad categorization of winter storm-driven precipitation and summer-convective precipitation is valid, very often, winter storms contain considerable convective precipitation that is not surface-based. This is manifested by intense precipitation of short duration during cyclonic-originated rain events.

2.2 REGIONAL AND LOCAL SCALE PROCESSES

Throughout B.C. (including the Lower Fraser Valley) topography plays a dominant role in influencing the distribution of precipitation. Windward slopes lift air masses (resulting in cooling and condensation) resulting in enhanced precipitation. Major leeward slopes are associated with sinking warming and drying of air, and therefore tend to have a rainshadow effect. The former effect is primarily responsible for the marked gradient in precipitation evident across the GVRD (see Figure 2-1). Lowest annual precipitation is found in the southwest (areas such as Tsawwassen and White Rock) and increases markedly with proximity to the North Shore mountains.

Evidence has emerged to suggest that large cities can enhance precipitation. There are four hypotheses concerning urban enhancement of precipitation:

- unstable conditions induced by the urban heat island enhance convective activity;
- increased convergence and turbulence caused by the rough urban surface enhance convection;
- addition of water vapour to the atmosphere in cities from the burning of fossil fuels increases precipitable water and through greater heat output and increased surface roughness there is higher convective activity; and
- an increase in condensation nuclei associated with the emission of pollutants in cities promotes precipitation formation.

Studies (predominantly in the USA) suggest that the enhancement of precipitation by cities occurs mostly downwind and is associated with convective events during summer. Figure 2-2 shows an increase in total annual precipitation at Vancouver Airport which began in 1946 and was combined with the nearby Steveston record which commenced in 1895. Such combining of records can only serve to illustrate trends, unless there is a special investigation into the two records, which has not been carried out. This trend is unlikely to be caused by urbanization effects as these stations are on the fringe of Vancouver and are on the windward side of the metropolitan area. No research has identified any cause and effect of urbanization on changes in rainfall intensity in Vancouver.

2.3 MICROSCALES

The formation of precipitation within clouds is complex and poorly understood. Changes in the availability and types of **condensation nuclei** (i.e. from natural sources and anthropogenic pollutants) and intensities of convection can all influence droplet size distributions within clouds and ultimately the amount and intensity of precipitation that emerges from clouds. The impacts of changes in the amount of condensation matter in the atmosphere (due to human emissions and land-use changes) on cloud cover and precipitation is an important dimension of climate change research.

In summary, there are myriad factors influencing atmospheric precipitation processes. In the GVRD two factors dominate the distribution of precipitation:

- the frequency, intensity and stormtracks of winter cyclonic systems determine in large part the total amount of precipitation delivered to the region; and
- topographic effects strongly control the spatial distribution and intensities of precipitation associated with this wintertime succession of cyclonic systems.

Section 3

Literature Review - Summary

3. LITERATURE REVIEW - SUMMARY

Appendix A provides a comprehensive review of literature addressing climate change and variability in western North America in general and southwestern British Columbia and the GVRD specifically. Section 3 is a summary of this appendix.

3.1 GENERAL CIRCULATION MODEL SCENARIOS

UNCERTAINTIES

Although **General Circulation Models** (GCMs), also known as Global Circulation Models, provide the best available tool for projecting the impacts of changes in greenhouse gas and **aerosol** concentrations on global climate it is important to recognise their significant shortcomings. Of most concern in the context of this report are:

- inability of GCMs to adequately model impacts at scale of GVRD; and
- greater uncertainties in precipitation prediction compared to that of temperature.

Together, these limitations imply that considerable caution should be exercised in interpreting the output of GCMs with respect to their precipitation projections. At best, they provide a guide to likely trends, the magnitude and detailed spatial distribution of which remain uncertain.

GCM RESULTS

Notwithstanding these concerns, there is broad agreement on the basis of both theory and the output of GCMs that enhanced greenhouse warming associated with the accumulation of greenhouse gases in the atmosphere will be accompanied by a more active global hydrological cycle.

Perhaps the most sophisticated modelling studies to date have been conducted using the Canadian Climate Centre Model. Simulations were conducted for the period 1990-2100 using a “state-of-the-art” atmosphere-ocean coupled model utilising a “transient” approach (in which the simulation evolves realistically with steadily increasing concentrations of greenhouse gases and aerosols). Principal findings are:

- Globally averaged precipitation varies little throughout the simulations (a 1% increase by 2050 and 4% by 2090 over the reference period 1975-95). However, there are significant changes in the distribution of precipitation temporally and spatially; and

- In the North Pacific, the emergence of an “El-Niño like” pattern dominates the enhanced CO_2 climate in the 21st century.

Extreme precipitation increases almost everywhere over the globe. Over southwestern B.C. 20-year return values for precipitation are projected to increase by less than 10 mm/ day by 2050 and by 10-20 mm/day by 2090. For comparison, extreme daily rainfall in the Vancouver area ranges from 90 to 135 mm/day. This implies an increase of 10 to 20% over the coming century and a possible increase in the frequency of extreme precipitation events. Increases in precipitation intensities, however, are thought to be more pronounced in the interior of southwestern B.C. and much diminished along the coast.

A trend in climate science is to present projections of increased precipitation in terms of quantifying the risk of threshold exceedance rather than deterministic expressions as above. A quantification of threshold exceedance risk will necessitate the establishment of a clear trend and an understanding of the underlying mechanism to allow trend extrapolation with confidence. This has not yet been performed for North America.

Global climate modelling has continued to increase in sophistication in recent years. The best models are able to reproduce our present global climate reasonably well (an important test of the ability of models to project future climates) and enable a realistic representation of important processes and feedbacks (e.g. coupling between the atmosphere and ocean). Model projections suggest that coastal B.C. is not a region likely to experience significant changes in precipitation climate compared with other regions (e.g. the southwestern USA, northern latitudes or eastern central eastern Pacific). However, the models do project a modest, but statistically significant increase in:

- winter precipitation;
- extreme events; and
- the frequency and intensity of El Niño episodes.

Current simulations suggest that these projections are reasonable expectations given our current understanding of oceanic and climatic forcings. It is expected that these expectations will be amended as models increase in sophistication.

3.2 IMPACTS OF PDO AND ENSO ON PRECIPITATION IN WESTERN NORTH AMERICA

The Pacific Ocean exerts a strong climatic signal worldwide. Due to the GVRD's location at the northeastern edge of the Pacific, climate is largely controlled by atmosphere-ocean interactions. The principal modes of climate variability are:

- El Niño Southern Oscillation (ENSO); and
- Pacific Decadal Oscillation (PDO).

El Niño events (which occur on average every 3-7 years) are part of a natural atmosphere- ocean oscillation in the Pacific basin and generally only operate to influence the winter and spring climates in a noticeable way. The impact of changing patterns of sea surface temperatures, precipitation and winds in the tropical Pacific can have a significant impact on the storm tracks in the mid-latitudes. Generally, El Niño winters are associated with increased precipitation south of 40°N (e.g. California) and less precipitation to the north (including southwestern British Columbia). During La Niña events, which are characterized by unusually warm sea surface temperatures in the western Pacific, southern Oregon and California receive lower than normal precipitation, while Washington and British Columbia record significantly increased precipitation. Variations of the Southern Oscillation Index are shown in Figure 3-1 together with the PDO Index. This figure shows that negative PDO indices often occur during times of positive SOI indices and vice versa. This means that El Niños are more common during periods of warm PDO, leading to the relatively common condition of drier and warmer winter conditions in B.C.

The PDO represents an ENSO-like pattern that occurs at longer time scales. The warm phase is associated with anomalously warm waters off the coast of western North America and cold water in the central Pacific. For coastal B.C. this means in general thinner snowpacks due to generally higher temperatures and generally a greater percentage of precipitation in the form of rain. The cold phase is the reverse with snow packs increasing in depth while precipitation totals maybe higher than in warm phases. Individual phases, although varying in duration and strength last for an average of 23 years. An entire cycle of the PDO (warm and cold phase) is typically therefore of 50-70 years duration as seen from evidence during the last 100 years. Evidence from tree-rings has been used to demonstrate that the PDO is not a recent phenomenon. It has clearly been an important part of the Pacific climate for the past 300 - 400 years (and in all likelihood well before that). At the time of this report, there is evidence that a switch has occurred from the last PDO warm phase (1977-1998) to a cold phase, but several more years of observation are needed to confirm this hypothesis. It is important to note that the precipitation trend analysis fall entirely within 1 cycle of the PDO and the results may be strongly influenced.

For western North America, the primary impact of ENSO and PDO is in changing storm tracks and hence the spatial distribution of precipitation. Studies suggest that the total precipitation delivered to the entire coastal region of western North America varies only by 10% of the average from year to year. However, in El Niño years that precipitation is unevenly distributed in favour of areas south of 40°N and in La Niña years the precipitation is delivered more to areas north of 40°N. The PDO has similar effects at longer timescales.

The ENSO also modulates the proportion of precipitation falling as rain and snow. In the GVRD during years with an El Niño receives precipitation of the order 5% less than long-term averages (“normal”). La Niña precipitation is of the order 10% above normal. Snow depth and snow water equivalent in the GVRD during El Niños is of the order 70% below normal whereas during La Niñas, it is characteristically 50% above normal. This effect arises from the influence of El Niño and La Niña on the mean winter temperature anomaly that is approximately +1°C and –1.0°C, respectively compared to normal.

ENSO and PDO are the two most important climatic "drivers" for the climate variability in Western North America, and account for up to 45% of the annual precipitation variance in southwestern B.C. The other 55% are a combination of factors that yet await identification and quantification. There is mounting evidence that ENSO and PDO influence not only the amount of local precipitation, but also the intensity, frequency and duration of extreme precipitation events. This aspect is further investigated in Section 5.

3.3 RAINFALL TRENDS IN SOUTHWESTERN BRITISH COLUMBIA

Climate variability associated with the cyclic patterns of ENSO and PDO dominate the historic record of precipitation and temperature in B.C. For example, the relatively dry period from 1977 to 1988 can be explained by a coincidence of a PDO warm phase and a higher frequency of particularly intense El Niños. These cyclic fluctuations are superimposed on a modest positive trend in annual precipitation over the past century in southwestern B.C. (10% of the mean value per century) which is not proven but is consistent with an enhanced hydrological cycle. It can be speculated that an enhanced hydrologic cycle would overcompensate for any dryness caused by any increases in the frequency of intense El Niños during the past quarter century.

A recent study suggests that this upward trend in annual precipitation in the central and southern interior of B.C. over the last century coincides with an increase in the frequency and intensity of North Pacific cyclones during the last 50 years (Graham and Diaz, 2001). Given that most of the precipitation and the most intense precipitation falls during winter, it is important to note that there has been no geographically consistent trend in winter precipitation in the Georgia Basin when precipitation is most critical. This is in contrast to the remainder of the southern B.C., where increases in average annual precipitation from 14% to 28% per century have been identified.

Although the trend in annual precipitation is reasonably clear, evidence for significant trends in extreme precipitation is weak. Results are somewhat contradictory and depend to some degree on the length of record considered. For the period 1950-94 in southwestern B.C. there is an overall increase in high intensity rainfall frequency associated with spring, summer and fall for 1950-94, while winter months show a slightly negative trend. At the century timescale this pattern is not evident.

However, most importantly, all studies suggest that the frequency of occurrence of higher precipitation rates (but not extremes) is influenced by circulation changes associated with the PDO and ENSO. For the Vancouver area, there is evidence of an upward trend in the number of days when rainfall intensities exceeded 10 mm/hr for durations less than one hour. This increase began in 1977 and coincides with the step-change from a cold phase to a warm phase PDO. If the step in rainfall intensities is not a coincidence it is reasonable to expect that a reversal in this trend will occur as a change in phase of the PDO may have occurred in 1998. The next 5 years may show whether the suspected phase change of the PDO affects precipitation intensities in the GVRD.

3.4 STREAMFLOW TRENDS

Change in river flow patterns is influenced by precipitation amounts, the intensity of cyclonic storms, the proportion of precipitation falling as rain, temperature during the melt season, and glacier mass balance. Streamflow is included in this study because it may indicate changes in precipitation intensities which may be correlated to changes in frequency and intensity of cyclonic storms.

Historically, record floods are usually associated with years of below average temperature and above average precipitation. An “ideal” mixture of conditions for flooding, particularly in urban watersheds with less than 50% impervious area, might occur when a PDO cold phase is superimposed by a La Niña event.

It should also be noted that most glaciers in B.C. have retreated over the past century and are likely to continue to do so in the long-term, even though short-term advances are conceivable. During the coming PDO cold phase it is conceivable that glacial retreat might slow or even cause a number of years with positive glacial mass balance. Further glacial recession will likely cause a lowering of base flow in glacierized watersheds and an earlier onset of spring runoff.

3.5 SNOW DEPTH AND SNOW WATER EQUIVALENT TRENDS

Recent analysis by CICS on changes in snow depth show decreases in snow depth for January, February, and March in the Georgia Basin, the southern Interior and the southern Coast Mountains. In addition, a decrease in the ratio of snow to rain has been detected over the past 50 years. It should be noted that snow depth measurements are a poor measure for changes in precipitation regimes because snow water content is influenced by the density of the snow. Record length (35 to 50 years in most cases) is also too short to allow meaningful projections.

Spring snowpack anomalies have been researched for British Columbia. It was found that anomalies from 1966 to 1976 are characterized by heavier-than-average anomalies for southern British Columbia while northern B.C. received lighter-than-average snow. From 1977 to 1992 snowpack conditions were lighter in southern B.C. and heavier-than-average in the northern B.C.

The differences in anomaly pattern and frequencies of synoptic types between the 1966-1976 and 1977-1992 periods accord with decadal-scale shifts in sea surface temperatures and atmospheric circulation pattern over the North Pacific, as reported in elsewhere in the literature. The shift in snowpack anomaly pattern following 1976 is consistent with reported shifts in glacier mass balance and rates of retreat and with streamflow fluctuations. In Section 4, snow water equivalent at Grouse Mountain was updated to 2001 and plotted together with PDO and ENSO phases.

These findings have little implications for the GVRD's stormwater and sewer infrastructure. However, they are very important for the prediction of water availability for the GVRD's water systems.

3.6 TEMPERATURE TRENDS

Temperature trends developed from long term records indicate that coastal B.C. has been warming at a rate of about 0.5^{o}C per century for average annual temperature while the southern interior of B.C. has warmed at a rate of 1.1^{o}C per century. This warming has occurred mostly due to a greater increase in minimum temperatures than maximum temperatures. For instance, annual average minimum temperatures have risen by about 0.9^{o}C on the coast with little change in annual average maximum daily temperature while in the interior of B.C. minimum temperatures have risen about 1.5^{o}C and annual average maximum temperatures have risen less than one degree.

The impact of these temperature rises on changes in precipitation has not been investigated at the local and GVRD scale. Increases in annual precipitation of 2 to 4% per decade over the interior of B.C. during the past 70 years are statistically significant and much larger compared to the smaller, statistically insignificant trend over the Georgia Basin. While the trends are consistent with greater annual precipitation in a warming climate, no cause and effect has been established.

Section 4

Data and Methods

4. DATA AND METHODS

This section addresses the type and number of data gathered for this study. Section 4.1 focuses on the selection of precipitation records. It is complemented with Appendix D. Section 5.1 addresses the proxy records used in this report.

4.1 SELECTION OF PRECIPITATION RECORDS

Rain data was selected from eleven rain gauge stations in Greater Vancouver. Of these eleven, eight are owned by the GVRD and three by the Meteorological Service of Canada (MSC). Two additional stations (DN15 and the City of North Vancouver's raingauge, operated by KWL) were included in the analysis for comparison with DN25. Stations are selected based on location quality and continuity of available data. As a minimum requirement the data record had to span 30 years. Table 4-1 lists the selected sites, their location, and their data availability. Appendix D provides more detailed information on the data used in this study.

Table 4-1
Rain Gauge Sites

Site Owner	Site Name	Site Location	Record Availability (during these years there may be incomplete data)
GVRD	VA01	Kitsilano High School	1958-1973 1976-1984 (max. annual intensities & monthly totals) 1987-2001
GVRD	VA04	Renfrew Elementary	1958-1984, 1986-2001
GVRD	CW09	Westburnco Reservoir	1950-1976, 1978-2001
GVRD	QT10	Coquitlam City Hall	1960-2001
GVRD	VA13	Stanley Park Yard	1950-1979, 1982, 1988-2001
GVRD	VW14	West Van. Municipal Hall	1959-1979, 1982-2001
GVRD	DN15	Cleveland Dam	1960-1983 (handwritten; not used in this study) 1992-2001
GVRD	DN25	Distr. N. Van. Municipal Hall	1964-2001
GVRD	BU31	Confederation Park	1950-1973, 1988-1997
CNV	KWL	W 16th Ave. KWL rooftop	1992-2001
MSC	Pitt Polder	Pitt Polder	1965-1999 2000-2001 (totals only; no intensities)
MSC	YVR	Vancouver Int'l Airport	1960-1999 2000-2001 (totals only; no intensities)
MSC	Surrey-Kwantlen	Surrey	1962-1999 2000-2001 (totals only; no intensities)

4.2 PROXY DATA

Instrumental records for rainfall intensity in the GVRD only extend back to the 1950s and 1960s. Even though some 40 years of data may be sufficient to detect short-term trends in monthly or annual rainfall intensities, it is inadequate to detect climate change. Section 2 detailed the importance of ENSO and PDO phenomena in determining temperature and precipitation in the Pacific Northwest. Within each ENSO or PDO cycle climatic trends can be expected. In order to project observed trends into the future, natural occurring oscillations such as PDO and ENSO must be understood which involves:

- comprehension of the evolution and driving forces of an oscillation such as change in ocean currents, salinity, winds etc.;
- demonstration that the amplitude of those oscillations has changed in a linear or non-linear fashion over time; and
- reasoning that this change in oscillation amplitude is pervasive and will continue into the future.

To attempt projections of an instrumental time series, the instrumental record needs to be extended backwards in time by proxy data discussed in the next subsection.

USE OF PROXY DATA

There are numerous indicators of past climates that extend the instrumental record. The most widely used for climate reconstruction are:

- ice cores that provide information on the temperature and atmospheric composition back to some 300,000 years;
- an analysis which examines the relation of tree pollen or other pollen to each other and thus is a surrogate of the composition of the vegetation in a region, which in itself mirrors climate to some degree;
- varve thickness (varves are annual accumulations of sediment in lakes) which is a representation of changes in sediment input to a lake by a stream, which itself mirrors rainfall or snowmelt to some degree; and
- dendroclimatology which uses the change in tree ring thickness or density that have been proven to be linked to changes in temperature or precipitation.

Of these methods, dendroclimatology has proven to be the most successful method for a time frame spanning several centuries. This method is also most appropriate for the purpose of this study because it includes interdecadal oscillations over a long enough period to detect any possible trends. The most important facet of dendroclimatology is the possibility of exact dating. Dendroclimatology is accurate to the year. This is vital to determine the exact year of the onset and end of an oscillation and thus reconstruct its phases. Dendrochronologic data and records are discussed and interpreted in Section 5.

4.3 SNOW WATER EQUIVALENT (SWE)

SWE data were gathered to identify any trends or cycles that may be correlated to precipitation intensity and to investigate the influence of PDO and ENSO on SWE. If correlations between SWE and precipitation intensity were to be found, trends in SWE, which are based on longer data records than precipitation intensity, could be used for precipitation intensity projections.

Snow water or springtime snowpack is a useful hydrological variable because it is measured at hundreds of snow courses throughout British Columbia at a wide range of elevations. Snow depth does not reflect total winter precipitation because rain and meltwater may be lost through drainage. Furthermore, water may be lost through sublimation from the top of the snow depth. For this reason the more meaningful variable snow water equivalent (SWE) was chosen.

The closest snowpack data to the GVRD are collected at Grouse Mountain at an elevation of approximately 1,100 m. Results from this analysis are summarized in Section 5.

4.4 STREAMFLOW

Long-term changes in streamflow are a good indication of changes in the precipitation regime which may affect the GVRD's infrastructure. Much like glaciers, however, streamflow also reflects changes in temperature because most large rivers in B.C. are dominated by snowmelt.

Analysis was conducted on two relatively small watersheds that have been gauged for extended time periods (31 to 90 yrs). Mackay Creek and Capilano River which drain mostly undeveloped watersheds of the North Shore Mountains of Vancouver. The results from these analyses are presented in Section 5.

4.5 DATA LIMITATIONS

DATA QUALITY

Data quality has a large impact on the results from the analysis in this report. Difficulties were encountered in data completeness, data transcription, data coherence and instrumentation. Data quality and data problems encountered are summarized in

Appendix D. This section focuses on general problems associated with precipitation projections and predictions.

UNCERTAINTIES IN PRECIPITATION PROJECTIONS

Fundamental differences exist in the character and origins of temperature and precipitation that influence their prediction. While temperature is a continuous property of the atmosphere, precipitation is a location specific event. In other words, temperature can be measured at all times, while precipitation can only be measured when it occurs. Furthermore, precipitation varies spatially and temporally by at least an order of magnitude more than temperature.

The four principal factors responsible for uncertainty in predicting precipitation are:

- temporal and spatial differences;
- data recording problems;
- different scales of atmospheric motion; and
- the non-linearity of the atmosphere.

Addressing uncertainty is an important issue in climate projections and is therefore receiving much attention in this study. The following section will explain the differences between prediction and projection.

PREDICTION VERSUS PROJECTION

The prediction of temperature and precipitation is accomplished using numerical models that simulate the atmosphere-ocean system including the processes occurring at the Earth's surface. Factors that are simulated in weather and climate prediction models include:

- topography;
- vegetative and snow ground cover;
- atmospheric circulation on the global, regional and local scales;
- airmass characteristics (such as atmospheric temperature profile, stability and moisture content);
- antecedent soil moisture and temperature; and
- oceanic temperature profile and ice cover.

Local physical processes, the surface energy and the surface water budget processes, including radiative exchange (airmass heating and cooling) and evaporation and evapotranspiration vary seasonally in frequency and intensity.

"Prediction" or "forecasting" suggests a high level of confidence. Weather predictions (or forecasts) are made for 1 to 10 days in advance and are "deterministic forecasts" (i.e. one prediction for a specific time and location) whereas climate "projections" are expressed in terms of changes from a reference climate, averaged over several decades over large areas. Thus, "projections" lack precision and reflect a lower level of confidence. This limitation suggests that a range of projections, derived from a number of different models, or from a number of different atmospheric forcing scenarios should be used rather than providing a single projection. While both predictions and projections are based on numerical and statistical methodology, there is greater uncertainty associated with projections.

PRECIPITATION PREDICTIONS AND PROJECTIONS

Precipitation results from two primary atmospheric processes:

- broad vertical motion in the atmosphere usually occurring at the interface between air masses and which results in continuous rain (e.g. rain lasting hours to days); and
- convection arising from atmospheric instability (e.g. showers lasting up to an hour).

Both processes may occur simultaneously and may be (but not necessarily) influenced by the underlying topography. The frequency and intensity of precipitation events varies geographically and temporally, even within the same weather system.

Over long time scale, periods of drought and excess precipitation are not uncommon. Causes of these events originate from persistent large-scale atmospheric circulation patterns.

Precipitation frequency and event intensity vary with the season. Predicting whether a particular month or season will be wet or dry is particularly difficult because the causes of variability on this time scale are poorly understood. In addition, the frequency and intensity of the precipitation process (continuous versus convective origin) is influenced by global atmospheric circulation patterns, the variations and interactions of which are also poorly understood on an annual time scale.

A further complication in predicting precipitation is the randomness of spatial occurrence, especially those events arising from convective activity where highly variable precipitation amounts are observed. Precipitation is greatly affected by strong topographic relief, being enhanced on the windward side and diminished on the downwind (lee) side. While the presence of mountains allows general statements to be made, such as "precipitation is more frequent and intense over higher terrain", the non-linear nature of the atmosphere precludes any definitive statement about predicting a specific location, intensity and amount of precipitation. The complexities of observing and characterizing representative precipitation in a location or over a region far exceed those of temperature.

PRECIPITATION VARIABILITY

Long-term (decades to century) projections of precipitation generated by General Circulation Models (GCMs) and known generally as "climate scenarios" contain far more uncertainty than daily weather forecasts or seasonal projections noted above. The coarse definition within the models (1,000s of km) means that topography is poorly represented. Topography of the GVRD is not represented at all. Furthermore, precipitation processes are not modelled directly as both synoptic scale and convective precipitation occurs at the sub-grid scale in GCMs. There is a limitation as to what can be accomplished with GCMs when the requirement is on a fine spatial (of the order kilometres) and temporal (daily) scale and in a region of complex terrain and surfaces.

For the GVRD this implies that GCMs are not able to make any specific predictions, but can only be used to identify general trends for coastal British Columbia.

UNCERTAINTIES IN PRECIPITATION TREND DETECTION

In addition to the difficulties in attributing causes to observed changes in amounts, durations and intensities of precipitation, significant uncertainties are associated with the analysis of precipitation data. These may be attributed to two main factors:

1. Precipitation is by nature intermittent, spatially variable ("patchy") and occurs in both liquid and solid form, which is in stark contrast to temperature which is continuous. This raises important issues concerning the spatial representativeness of precipitation data from individual stations.

2. Precipitation measurement is associated with significant errors. Rain gauge errors are primarily associated with undercatch due to wind effects and evaporative losses. For example, at wind speeds of 3 m/s standard Canadian gauges without windshields (Hellman) 10% of the measured value has to be added for rain and 120% of the measured value has to be added for snow to obtain the true amounts. Mekis and Hogg (1999) have produced a rehabilitated (corrected) data set that is used for the major Canadian studies described below. No such corrections are made for GVRD data.

In addition, trend analysis of precipitation data is hampered by:

1. Site changes, instrument changes, and "leverage" from near-extremes near the beginning and ends of observed series. These changes are often poorly documented and seldom considered in analyses (with the exception of Mekis and Hogg, 1999). However, they may significantly influence trend analyses. Changes over a period of time in the wind environment around a measurement site due to long-term urbanization (e.g. cutting of trees, erection of structures) may reduce mean wind speed, increase turbulence, increase catch in rain gauges and therefore produce an apparent upward trend in precipitation. Furthermore, it is sometimes noted that errors

can occur in the transferral of data from handwritten records or strip charts into digital form. This type of error is very difficult to detect unless random checks are performed.

2. Analyses of hydrologic time series are always affected by the length of record considered (i.e. the time "window"). Often, trends apparent in a short record are discovered to be part of a cyclic pattern apparent at longer time scales. This suggests that considerable caution needs to be exercised in the extrapolation of apparent trends. This point will be discussed in more detail in the following subsection In addition, leverage due to the strongly departing values near the beginning and end of the record may bias the data record.

4.6 TIME SERIES ANALYSIS

In time series analysis it is assumed that the data consist of a systematic pattern (usually a set of identifiable components) and random noise (error) which usually makes the pattern difficult to identify. Most time series analysis techniques involve some form of filtering of noise in order to make the signal (or patterns) more coherent.

Most time series patterns can be described in terms of two components: trend and seasonality. The former represents a general systematic linear or non-linear component that changes over time and may be repeated within the time range captured by our data. The latter may have a formally similar nature however, it repeats itself in systematic intervals over time. Those two general classes of time series components may coexist in environmental time series data such as used in this study.

There are no proven "automatic" techniques to identify trend components in the time series data; however, as long as the trend is monotonic (consistently increasing or decreasing) that part of data analysis is typically not very difficult. If the time series data contain considerable errors, then the first step in the process of trend identification is smoothing discussed in the next subsection.

It is important to realize that there are a plethora of time series analysis methods available. However, each analysis requires an understanding of the underlying mechanism, which, in the case of this study, may be random. For this reason, emphasis is placed on simple visual techniques rather than sophisticated mathematical treatment.

SMOOTHING

Smoothing always involves some form of local averaging of data such that the non-systematic components of individual observations cancel each other out. The most common technique is moving average smoothing which replaces each element of the series by either the simple or weighted average of n surrounding elements, where n is the width of the smoothing "window". Medians can be used instead of means. The main advantage of median as compared to moving average smoothing is that its results are less biased by outliers (within the smoothing window). Thus, if there are outliers in the data (e.g., due to measurement errors), median smoothing typically produces smoother or at least more "reliable" curves than moving average based on the same window width. The main disadvantage of median smoothing is that in the absence of clear outliers it may produce more “jagged” curves than moving average and it does not allow for weighting. For this reason, mean smoothing was used as the preferred technique.

The results from smoothing techniques are summarized in Section 5.

CUMULATIVE DEPARTURES FROM THE MEAN

Long-term trends in highly variable data may be identified by plotting cumulative departures from the mean. The departure is expressed as a percentage of the mean to facilitate comparison between records. A sequence of above-average years appears as an upward trend, while a sequence of below average years appears as a downward trend. A flat plot indicates a period of average conditions. Comparisons of plots from several stations can reveal regional heterogeneity or homogeneity of trends.

It should be noted that cumulative departures from the mean have significant disadvantages and should therefore not be used in isolation when analysing data. Cumulative departure from the mean curves always show some cyclicity which cannot be attributed to cycles in hydrological processes but to the underlying mathematics. Comparing cumulative departure plots of different lengths of time is unscientific because the different means may have opposite phases for the same period. In other words, the same time series, if split into random sections, may show trend reversals if compared to the total series. For this reason, cumulative departure from the mean plots were only used to compare time series of similar record length.

Cumulative departure from the mean plots were used for monthly and annual data of precipitation intensities as well as in investigating changes between the summer and winter months.

LINEAR REGRESSION ANALYSIS

The general purpose of linear regression analysis is to learn more about the relationship between a predictor variable (in this case time) and a criterion (precipitation intensity) variable. Linear regression analysis also determines the extent to which values of the two variables are “proportional” to each other. It allows the identification of a statistically significant trend and is commonly used in statistical analysis to identify linear relationships between two variables. The major conceptual limitation of all regression techniques is that one can only ascertain relationships, but never be sure about underlying causal mechanism.

Linear regression analysis produces a line that provides the best fit through the analysed data. This line is defined as having the lowest sum of squared distances between the data points and the line. It is therefore referred to as the least-squares regression line that can quantify the strength of the linear relationship between two variables (time and precipitation intensity in this study). Quantification is expressed as Pearson's correlation coefficient, r, or its derivative, r^2, which is called the coefficient of determination. R or r^2 ranges between –1 and 1. A high negative value indicates a strong negative correlation between two factors, while a high positive value indicates a strong positive correlation. A value of zero indicates no association at all.

To conclude a strong linear relationship between two variables it is necessary to test whether their correlation coefficient or coefficient of determination is statistically significant. The simplest test is to see whether the regression line is significantly different from zero. Usually a level of 95% significance is used for linear regression analyses. Linear regression analysis was used for all data sets.

Section 5

Analysis – Proxy Data, Snowpack and Streamflow

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5. ANALYSIS – PROXY DATA, SNOWPACK AND STREAMFLOW

This section forms the backbone of this study. It summarizes the findings of precipitation intensity data analysis and attempts interpretation of results. It should be read in conjunction with Appendix B.

Section 5 is structured in four subsections, of which (Section 5.3 and 5.4) were added since the draft report was issued in April 2002. Section 5.1 discusses the results from the proxy data analysis. Section 5.2 focuses on changes in streamflow and snow pack, both surrogates for precipitation changes. Section 5.3 summarizes the results of the time series analysis of annual and monthly precipitation data. Section 5.3 is a summary of changes in the frequency of high intensity precipitation events. Section 5.4 attempts to interpret the findings from Section 5.2 and 5.3 and discusses possible extrapolation of findings.

5.1 PROXY DATA

This subsection focuses on the analysis and interpretation of proxy data introduced in Section 4.

TEMPERATURE

Temperature decline during a period known as the **Little Ice Age** (LIA, 1300 to 1850 AD) has been well documented. Investigations of glacial moraines in the Cascade mountains in Washington imply that temperatures during the LIA were by approximately 1.0° Celsius lower than during the 20th century.

Dendroclimatology allows a year-by-year temperature reconstruction into the LIA with the possibility of correlation of the past 100 years with the instrumental record. Figure 5-1 shows reconstructed mean annual temperature from Longmire, Washington immediately south of Mount Rainier (Graumlich and Brubaker, 1985). Longmire is only about 300 km south of Vancouver and is affected by similar synoptic weather pattern. Furthermore, samples sites for this investigation are as close as 150 km east of Vancouver in the Washington Cascade Range. Figure 5-1 shows distinct periods of higher or lower average temperatures. It also clearly shows above normal temperatures since 1900. The LIA ended around 1850.

Other dendroclimatologically derived temperature records in the western United States show little resemblance in the 17th, 18th and the first part of the 19th century, which may be due to different responses of various species to changes in temperature. However, there is a coherent rise in temperature from the proxy records beginning in the mid-nineteen hundreds which mark the end of the LIA. From about 1850 to 1900, temperatures recovered from LIA lows but were probably unaffected by anthropogenetically caused climate change. The effects of climate warming due to greenhouse gas emissions began probably around 1900.

PRECIPITATION

As with temperature, precipitation can be reconstructed from dendrochronologic records. Instead of searching for sites where tree growth is mostly influenced by temperature fluctuations, site and species choice for precipitation reconstruction must be chosen accordingly. Graumlich (1987) assembled proxy data of precipitation for three regions within the Pacific Northwest using drought-sensitive conifers from sites in northern Washington within 200 km of Vancouver to northern California (Figure 5-2 a**,** b, c).

Figures 5-2 a, b, c show that northern California and southern Oregon display different precipitation responses than northern Oregon and Washington. This observation is in accordance with ENSO records that show wetter periods in the first regions while drier conditions prevail in the latter. The same is true for the reverse situation. The reason for this observation is the deflection of large synopic storms south of approximately 44° latitude during El Niño events and north of 44° during La Niña events.

Figure 5-3 shows a 500-year record of dendrochronologically derived data of snow depth and precipitation (July) from the Forbidden Plateau on Vancouver Island from 1500 to 2000. The graph does not show any systematic long-term trend in either snow depth or precipitation.

SUMMARY

The most important results are:

- Average temperature has changed significantly over the past few hundred years. The Little Ice Age temperatures were about 1° C lower than during the 20th century.
- The mean precipitation of the period reconstructed by dendrochronology (1670 – 1900) does not differ significantly from the mean of the instrumental record (1900 to present), implying that to date there is no pervasive trend in the long-term precipitation pattern in the western North America.
- Episodes of extended dry and wet periods are present in all precipitation reconstructions but the variations of precipitation from the Columbia Basin and the Western Lowlands are out of phase with the Southern Valleys.
- Years of extreme drought are spatially homogenous (i.e. occur throughout the Pacific Northwest and southern B.C.) indicating that they are caused by circulation features of sufficient size and persistence to affect the Pacific Northwest and southern B.C. as a whole.

It has been recognized that climate undergoes interdecadal shifts during the 20th century. These regime shifts have far-reaching socio-economic impacts. PDO records have been extended beyond the instrumental records by tree-ring chronologies from Southern California and Baja. The principal results from these PDO studies are:

- Decadal reversals of Pacific climate have occurred throughout the last four centuries.
- A 23-year oscillatory mode was identified from the proxy PDO at all stations. This is consistent with circulation time of the Pacific gyre as suggested by simulation models. Given the understanding of a 23-year cycle, it is very probable that a shift towards another PDO cool phase has occurred around 1998.
- There is a transition in the 1800s towards greater temperature anomalies associated with PDO regimes which coincides with a 19th to 20th century increase in interannual variability of ENSO.
- Three of the four most significant ENSO episodes of the past 330 years occurred during the 20th century. There is a low probability that this observation is due to random fluctuations, indicating that this change may be linked to anthropogenic greenhouse gas emissions.
- Anthropogenically-caused atmospheric warming could have caused changes in natural large-scale modes of climate variability. More pronounced PDO and ENSO cycles may be associated with anthropogenic changes in the 20th century.

The following subsection will investigate other hydroclimatic indices such as snow pack and streamflow.

5.2 SNOW PACK AND STREAMFLOW

SNOW PACK

Figure 5-4 shows the April snow water equivalent (SWE) at Grouse Mountain from 1936 to 2001. PDO and ENSO phases are also shown on the figure. It is evident from the graph that PDO and ENSO exert strong influence on SWE at Grouse Mountain. Particularly in the last PDO warm phase from 1977 to 1998 there has been a significantly lower-than-normal SWE at Grouse Mountain, which highlights the importance in Pacific oscillations for the availability of water in the GVRD.

STREAMFLOW

In the Canadian Cordillera, the period from 1920 to the late 1940s was dominated by low runoff and small floods. From about 1950 to 1980 higher runoff and floods were observed during a time when precipitation totals increased 10-20% over the normal during fall and winter. The earlier period coincides with a PDO warm phase, whereas the latter period coincides with a PDO cool phase. It is important to note that streamflow response is amplified by about 50% to changes in precipitation amounts. Since about 1980 (PDO warm phase), the frequency of floods has been lower.

Fraser River has the longest streamflow record in British Columbia. A number of significant observations have been extracted from previous studies:

- seasonal changes in the timing and volume of the Fraser River flow are occurring earlier in the year on average;
- flow is higher after a La Niña winter and peak flows arrive earlier in the year following an El Niño event; and
- there is no significant trend in the date of the height of peak flow from 1912 to 1998.

The absence of significant trends in extreme precipitation in southwestern Canada are largely confirmed by studies of streamflow for the past 30-50 years. Southern B.C. is not experiencing more extreme hydrological events (although there are significant changes in the timing of ice break-up and spring snowmelt).

The following includes streamflow analyses of Mackay Creek, Coquitlam and Capilano rivers. The latter two are regulated which implies that only those streamflow data were used that was obtained from upstream gauges of the reservoirs.

Mackay Creek

Figure 5-5 shows that the maximum annual and maximum instantaneous discharge of Mackay Creek have not changed significantly over time. Mackay Creek is the smallest gauged watershed on the North Shore Mountains and should therefore be the most responsive to changes in precipitation intensity that was superimposed from station DN25. The past five years of precipitation intensity data from this station are questionable as discussed at the end of this section.

Significant development has taken place in the lower Mackay Creek watershed from the 1950s to 1980s which should increase at least the peak floods. Figure 5-5 shows no trend in either direction. This may be due to a lack in significant changes in precipitation, or due to the fact that precipitation intensities are not necessarily reflected in stream runoff in systems where rainfall is buffered by vegetation and soil cover. The fact that large parts of the lower watershed have been made less pervious indicates that peak flows may actually have decreased.

Coquitlam River and Capilano River

The inflow of Coquitlam River into Coquitlam Lake has been recorded since 1954 by BC Hydro. Capilano River has one of the longest unregulated streamflow records in British Columbia. Figure 5-6 shows that the mean annual flow of Coquitlam River has slightly decreased over the past 40 years, while mean annual flow at Capilano River has remained largely constant. Only since the early 1990s has there been an upward trend in runoff.

When considering only maximum daily flows, an upward trend can be detected for Capilano River since 1977, which coincides with a change from a PDO cool phase to a PDO warm phase (Figure 5-7). No such change could be detected for Capilano River. It appears that there is a general downward trend in maximum daily flows at least during the last cool phase which lasted from about 1947 to 1977, and a general upward trend in the last warm phase which lasted from about 1977 to at least 1998. This conclusion, however, is not confirmed by Mackay Creek, which does not have a record long enough to span an entire PDO cycle (approximately 50 years). A downward trend during PDO cool phases is contradictory to the understanding that floods should be more frequent and of higher magnitude during PDO cool phases. A conclusive answer as to the correlation between PDO phases and streamflow response can therefore not be provided without further study. No correlations were found between runoff and precipitation intensities.

SUMMARY

In summary, changes in precipitation intensity evident in the instrumental record are poorly correlated to maximum daily flows of small stream on the North Shore of Vancouver. There seems to be a weak correlation between PDO phases and maximum daily flows for some rivers but other forcings such as ENSO events are likely to obscure a clear PDO signal in streamflow. It is unlikely that any changes in precipitation intensity will have significant impacts on mean or maximum annual streamflows.

Section 6

Analysis – Observed Precipitation Data

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6. ANALYSIS - OBSERVED PRECIPITATION DATA

Three principal techniques were used to identify and quantify trends in the data:

- smoothing functions;
- cumulative departures from the mean; and
- linear regression analysis.

The results from these analyses are discussed below.

6.1 SMOOTHING

In this section, the plotted data are visually assessed as to trends in the data record. For this assessment data are plotted monthly and annual with moving averages, linear trendlines and cumulative departures from the mean superimposed. This method is useful in identifying trends, while allowing a precursory look at possible outliers. The raw monthly data plots also allow a visual assessment whether a significant increase in high intensity precipitation events has occurred.

Table 6-1
Summary of Precipitation Trend Analysis for all Stations

Stations	**Monthly**			**Annually**			**Seasonal Differences**
Intensities	5,10,15 min.	30 min,1,2 hrs.	6,12,24 hrs.	5,10,15 min.	30 min. 1,2 hrs.	6,12,2 hrs.	
DN 25	no trend	no trend	no trend	no trend	**positive**	no trend	none
VW 14	no trend	no trend	no trend	no trend	**positive**	none	none
QT 10	no trend	no trend	no trend	no trend	no trend	no trend	oop 5-15 min.
VA 4	no trend	no trend	no trend	no trend	no trend	no trend	none
VA 01	no trend	no trend	no trend	no trend	no trend	no trend	oop 12,24 hrs.
CW09	no trend	no trend	no trend	no trend	no trend	no trend	oop 5-15min.
VA13	no trend	no trend	no trend	no trend	no trend	no trend	oop 5-15min.
BU31	no trend	no trend	no trend	no trend	no trend	no trend	none
Pitt Polder	no trend	no trend	no trend	no trend	no trend	no trend	oop 5-15min.
Surrey Kwantlen	no trend	no trend	no trend	no trend	no trend	no trend	oop 12 hrs.
YVR	no trend	no trend	no trend	no trend	no trend	no trend	oop 6-24 hrs.

Notes:
1. For DN25 the data from 1995 – 2001 were removed because of bias introduced by the cooling tower.
2. **No trend** means that the linear regression analysis did not yield statistical significance at the 95% significance level.
3. **Oop** stand for “out-of-phase” and indicates that seasonal deviations from the mean are in opposite directions

Table 6-1 shows that except for the 1 and 2 hour durations at DN25 and VW14, no statistically significant trends were found. In some cases, seasonal trends plotted as cumulative departures from the mean precipitation intensities were in opposite directions which implies that while precipitation intensities rose for the summer months, they decreased during the winter months or vice versa. No obvious reasons for this behaviour are apparent and more specific analyses would be needed to address this issue.

Should it be found in the future that there is indeed an overall increase in 1 and 2 hour duration precipitation intensities, primarily those watersheds with more than 50% impervious areas are likely to respond to those changes. This would include the majority of small urban watersheds in the GVRD.

In summary, there is very little evidence for a systematic change in precipitation intensities apart from a weak increase on the North Shore, suggesting that topography may play a role in this increase. Trends are too weak and too isolated to allow any meaningful extrapolation of trend lines without understanding the underlying mechanisms.

The rainfall intensity data were further analysed by month for three stations (DN 25, VW 14, and YVR). The reason for this analysis was to detect specific months that display strong trends. The month may then provide information as to the type of weather system that seemed to have caused the trend.

At DN25 (Appendix B), the month of June seems to explain much of the increasing trend detected in the above analysis. Starting in the 1990s, June rainfall intensities have increased until the present. This effect, however, seems to diminish with durations in excess of 2 hours, which is in accordance with the trend of increasing precipitation intensity described in this subsection. June precipitation is usually caused by convective cells that may or may not be associated with frontal systems. Extreme June precipitation is characterized by high intensity – short duration precipitation events, which may explain the diminishing effect for durations in excess of 2 hours. Even minor increases in the intensity of extreme June rainfall events could have severe consequences for small watersheds with a high proportion of impervious areas. Subsection 6-2 will investigate whether the month of June is of importance for other GVRD or MSC stations.

CUMULATIVE DEPARTURES FROM THE MEAN

In general, very few systematic similarities were found in the cumulative departure from the mean graphs. These are summarized in Table 6-2.

Table 6-2
Summary of Cumulative Departures from the Mean for all Stations

Stations	Monthly	Trend	Annually	Trend
DN 25	1964 - 1977 1977 - 1983 1994 - present	positive negative positive	1964 – 1977 1994 – present	positive positive
VW 14	1957 - 1972 1993 - 1998 1998 - 2001	negative positive negative	1957 – 1972 1982 - 1998	negative positive
QT 10	1957 - 1977 1994 - 2001	negative positive	1965 - 1982	negative
VA 4	1972 - 1979 1979 - 1985 1985 - 1994 1994 - 2001	negative positive negative positive	NSC	NSC
VA 01	NSD	NSD	NSD	NSD
CW09	1992 - 1995 1995 - 1997	negative positive	NSC	NSC
VA13	NSD	NSD	NSD	NSD
BU31	NSD	NSD	NSD	NSD
Pitt Polder	1995 - present	positive	1992 - present	positive
Surrey Kwantlen	1962 - 1972 1993 - 1997	negative positive	1972 - 1982	positive
YVR	1965 - 1977 1995 - present	negative positive	1962 - 1990 1995 - present	negative positive

Only changes detectable over most durations were included in this table. Usually, trends in cumulative departures are only detectable over the 5 min. to 2 hr. durations.

NSD mean “not sufficient data” to allow reliable calculation of the mean.

NSC means “no systematic changes” in the data record

It appears that before the mid-1970s there was an overall downward trend in monthly precipitation, whereas there was a positive trend in the last 6 years or so. Only the latter trend can be observed at most stations. Given its very short duration and the lack of a meteorological or climatological reason, no projection of this trend can be made.

6.2 LINEAR REGRESSION ANALYSIS

In this study, linear regression analysis was used to find trends in the time series. This was accomplished by creating a linear regression between time and precipitation intensity for all available precipitation intensity durations. Details of the method are explained in Section 4.

Annual Maxima

Graphically the linear regressions are shown as a straight line on the monthly and annual rainfall intensity data shown in Appendix B. The data were subsequently tested for statistical significance and summarized in Table 6-3.

Table 6-3
Summary of Linear Regression Analysis

GVRD Station DN25									
Duration	5 min	10 min	15 min	30 min	1 hr	2 hrs	6 hrs	12 hrs	24 hrs
R^2	0.13	0.12	0.12	0.12	**0.14**	**0.18**	0.00	0.00	0.04
SE	2.9	2.1	1.7	0.9	0.4	0.3	0.2	0.2	0.2
GVRD Station VW 14									
R^2	0.02	*0.02*	0.07	0.1	**0.12**	**0.13**	*0.06*	*0.07*	*0.05*
SE	2.7	*3.6*	1.6	0.9	0.5	0.3	*0.4*	*0.5*	*0.4*
GVRD Station QT10									
R^2	0.01	0.03	0.03	0.03	0.08	0.08	0.01	0.00	0.06
SE	3.0	2.5	2.2	1.3	0.7	0.3	0.2	0.1	0.1
GVRD Station VA4									
R^2	0.00	*0.00*	0.00	0.00	0.00	0.00	0.00	*0.00*	*0.00*
SE	0.5	*0.5*	0.3	0.2	0.1	0.1	0.1	*0.1*	*0.1*
GVRD Station VA01									
R^2	0.02	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0
SE	0.5	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0
GVRD Station CW09									
R^2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SE	0.7	0.5	0.4	0.3	0.2	0.1	0.1	0.1	0.0
GVRD Station VA13									
R^2	0.02	*0.02*	*0.03*	0.03	0.03	*0.04*	*0.03*	*0.03*	*0.02*
SE	0.5	*0.5*	*0.3*	0.2	0.2	*0.1*	*0.1*	*0.1*	*0.0*
GVRD Station BU31									
R^2	0.03	0.03	0.04	0.05	0.07	0.07	0.05	0.05	0.04
SE	0.5	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.0
MSC Station Pitt Polder									
R^2	0.05	0.04	0.05	0.03	0.01	0.00	0.06	0.05	N/A
SE	3.9	2	1.3	0.8	0.5	0.3	0.3	0.2	N/A
MSC Station Surrey Kwantlen									
R^2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N/A
SE	2.5	1.9	1.6	1	0.5	0.3	0.2	0.2	N/A

GVRD Station DN25									
Duration	5 min	10 min	15 min	30 min	1 hr	2 hrs	6 hrs	12 hrs	24 hrs
MSC Station Vancouver Airport									
R^2	0.08	0.09	0.04	0.04	0.08	0.09	0.06	0.00	0.03
SE	2.2	1.7	1.4	0.9	0.5	0.3	0.2	0.1	0.1

Notes:

- Data after 1995 have been excluded for DN25 because of strong bias (see following subsection).
- SE is the standard error of the mean. It is the theoretical standard deviation of all sample means of size n drawn from a population and depends on both the population variance (sigma) and the sample size (n).
- R^2 is the coefficient of determination It is an indicator of how well the model fits the data (e.g., an R^2 close to 1.0 indicates that almost all of the variability is explained with the variable specified in the model.
- Bold numbers are statistically significant at $\alpha = 0.05$ (95% confidence).
- Numbers in italics indicate that significant data gaps exist which violates basic statistical assumptions.

The data from Table 6-3 indicate that the only statistically significant trends are observed for DN25 and VW14 for the 1-hour and 2-hour durations. This conclusion is in accordance with the visual assessment from smoothing techniques. There is no apparent climatological reason that explains this trend. Should it continue in the future, a topographically enhanced control mechanism is likely.

Monthly Maxima

The annual maxima show little correlation as shown in the previous subsection. The data are now further stratified to investigate whether trends can be deciphered for individual months. To probe for possible trends, linear regression analysis was repeated for each month for all stations. To make the data manageable, only the 5 min, 15 min, 1 hr and 6 hour durations were investigated. The results of this are summarized in Table 6-4.

Table 6-4 a Linear Regression Results For Each Month – DN25

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.01	0.00	0.00	0.00	0.00	**0.24**	0.04	0.00	0.00	0.11	0.01	0.07
	P	0.72	0.81	0.73	0.89	0.75	**0.01**	0.27	0.83	0.75	0.07	0.58	0.15
15 min	r^2	0.02	0.01	0.04	0.01	< 0.001	**0.21**	0.09	0.00	< 0.001	0.11	0.02	***0.14***
	P	0.47	0.68	0.31	0.53	0.97	**0.01**	0.10	0.90	0.94	0.07	0.43	**0.04**
1 hr	r^2	0.01	0.02	0.13	**0.21**	0.04	**0.16**	0.00	0.02	0.02	0.10	**0.28**	0.09
	P	0.71	0.47	0.06	**0.01**	0.31	**0.03**	0.85	0.47	0.49	0.09	**0.00**	0.12
6 hr	r^2	0.00	0.02	0.00	0.02	< 0.001	0.02	0.01	0.01	0.12	0.01	**0.31**	0.01
	p	0.88	0.49	0.72	0.50	0.97	0.46	0.69	0.67	0.06	0.59	**0.00**	0.72

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk W test).

Table 6-4 b Linear Regression Results For Each Month – VW14

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.03	**0.19**	0.03	0.02	0.00	**0.11**	0.05	0.07	0.00	0.00	0.01	0.01
	P	0.34	**0.01**	0.25	0.39	0.84	**0.04**	0.20	0.13	0.76	0.87	0.67	0.65
15 min	r^2	0.01	**0.25**	0.06	0.06	0.01	**0.16**	0.02	0.02	0.01	0.01	0.01	0.03
	P	0.59	**0.00**	0.11	0.12	0.63	**0.02**	0.43	0.42	0.62	0.53	0.68	0.27
1 hr	r^2	0.02	***0.24***	0.09	0.06	0.06	**0.21**	0.01	0.01	< 0.001	0.01	0.02	0.02
	P	0.42	**0.00**	0.05	0.14	0.16	**0.01**	0.71	0.62	0.93	0.58	0.38	0.44

Notes: Rainfall intensity data for the 6-hour duration were incomplete. Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk W test).

Table 6-4 c Linear Regression Results For Each Month – QT10

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.07	0.01	0.01	< 0.001	0.09	0.06	0.01	0.00	0.06	0.00	0.01	0.00
	P	0.10	0.51	0.51	0.87	0.05	0.12	0.58	0.89	0.13	0.89	0.66	0.78
15 min	r^2	0.05	< 0.001	0.01	0.00	**0.12**	0.07	0.02	0.00	0.02	0.01	0.03	0.00
	P	0.15	0.96	0.62	0.88	**0.03**	0.08	0.35	0.89	0.37	0.57	0.32	0.89
1 hr	r^2	0.03	0.08	0.05	0.00	**0.15**	0.07	0.04	0.01	0.02	0.00	0.02	0.00
	P	0.27	0.07	0.16	0.85	**0.01**	0.10	0.23	0.54	0.33	0.86	0.39	0.78
6 hr	r^2	< 0.001	***0.19***	0.07	0.01	**0.12**	0.06	0.06	0.00	0.03	0.00	0.02	0.02
	P	0.95	**0.00**	0.10	0.57	**0.02**	0.13	0.12	0.73	0.27	0.79	0.43	0.44

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk W test).

Table 6-4 d Linear Regression Results For Each Month – VA4

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.07	0.02	0.01	0.05	0.02	0.02	< 0.001	0.04	0.01	**0.12**	0.01	0.00
	p	0.09	0.42	0.57	0.19	0.44	0.39	0.95	0.25	0.52	**0.03**	0.47	0.88
15 min	r^2	**0.10**	0.04	0.01	0.04	0.04	0.06	0.01	0.03	0.02	**0.12**	0.06	< 0.001
	p	**0.04**	0.22	0.58	0.25	0.20	0.13	0.50	0.31	0.38	**0.02**	0.12	0.96
1 hr	r^2	0.07	0.16	0.01	0.00	**0.19**	0.08	0.02	0.02	0.01	**0.09**	0.10	0.02
	p	0.10	0.01	0.60	0.79	**0.01**	0.09	0.36	0.42	0.62	**0.05**	0.04	0.40
6 hr	r^2	0.00	***0.28***	0.03	0.01	***0.15***	0.07	0.03	0.00	0.01	0.02	0.09	0.01
	p	0.78	**0.00**	0.35	0.61	**0.04**	0.17	0.39	0.91	0.63	0.46	0.12	0.57

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk W test).

Table 6-4 e Linear Regression Results For Each Month – VA01

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.01	0.00	0.01	**0.17**	0.01	**0.13**	0.02	0.02	0.03	0.02	< 0.001	0.09
	p	0.61	0.77	0.61	**0.02**	0.50	**0.04**	0.45	0.42	0.35	0.50	0.88	0.08
15 min	r^2	< 0.001	0.04	0.00	0.11	0.02	0.07	0.02	0.02	0.01	0.02	0.01	0.09
	p	0.92	0.27	0.76	0.05	0.42	0.13	0.44	0.40	0.51	0.44	0.51	0.09
1 hr	r^2	0.00	***0.15***	0.01	0.08	0.05	0.02	0.05	< 0.001	< 0.001	0.01	0.07	0.01
	p	0.73	**0.03**	0.59	0.10	0.20	0.40	0.21	0.93	0.95	0.58	0.14	0.53
6 hr	r^2	0.01	***0.13***	0.07	0.02	0.06	0.05	0.05	0.00	0.04	0.00	0.05	< 0.001
	p	0.59	**0.04**	0.14	0.40	0.18	0.22	0.21	0.84	0.25	0.77	0.21	0.97

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test).

Table 6-4 f Linear Regression Results For Each Month – CW09

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	< 0.001	***0.40***	***0.19***	0.02	0.00	0.02	0.00	0.07	0.03	0.03	0.11	0.01
	p	0.96	**0.00**	**0.05**	0.51	0.78	0.58	0.87	0.24	0.44	0.47	0.13	0.61
15 min	r^2	0.02	0.19	0.12	0.01	0.01	0.03	0.02	0.03	0.06	0.11	0.02	0.09
	p	0.50	0.06	0.13	0.67	0.74	0.44	0.56	0.45	0.28	0.14	0.58	0.18
1 hr	r^2	0.04	***0.23***	0.03	0.05	< 0.001	0.03	0.00	< 0.001	0.17	0.13	0.05	0.06
	p	0.40	**0.03**	0.49	0.34	0.96	0.43	0.89	0.98	0.07	0.10	0.30	0.28
6 hr	r^2	0.11	***0.34***	0.01	0.02	0.02	< 0.001	0.03	0.02	0.15	0.07	0.12	0.01
	p	0.15	**0.01**	0.67	0.52	0.52	0.95	0.45	0.57	0.08	0.25	0.11	0.63

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test).

Table 6-4 g Linear Regression Results For Each Month – VA13

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.00	0.02	0.01	**0.11**	**0.13**	**0.18**	0.03	0.00	0.01	< 0.001	**0.12**	0.00
	p	0.88	0.42	0.87	**0.03**	**0.02**	**0.01**	0.31	0.88	0.47	0.96	**0.02**	0.75
15 min	r^2	0.01	0.01	0.04	**0.22**	**0.14**	**0.21**	0.01	< 0.001	0.02	0.00	0.08	0.00
	p	0.54	0.61	0.23	**0.00**	**0.01**	**0.00**	0.63	0.92	0.34	0.82	0.05	0.78
1 hr	r^2	**0.16**	0.02	0.01	**0.16**	**0.20**	**0.14**	0.02	0.00	0.03	0.00	**0.13**	0.04
	p	**0.01**	0.40	0.63	**0.01**	**0.00**	**0.02**	0.34	0.79	0.29	0.82	**0.02**	0.22
6 hr	r^2	**0.21**	0.07	0.01	0.08	**0.14**	**0.13**	0.09	0.00	0.02	0.01	0.06	0.09
	p	**0.00**	0.11	0.56	0.09	**0.02**	**0.03**	0.08	0.84	0.45	0.48	0.14	0.07

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test) (none).

Table 6-4 h Linear Regression Results For Each Month – BU31

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.05	0.05	0.11	0.09	0.11	**0.20**	0.01	0.05	0.06	0.06	0.11	0.11
	p	0.19	0.22	0.06	0.09	0.06	**0.01**	0.56	0.20	0.16	0.17	0.05	0.06
15 min	r^2	***0.21***	0.06	**0.18**	**0.16**	0.10	**0.15**	0.02	0.03	0.09	**0.18**	**0.15**	**0.13**
	p	**0.01**	0.15	**0.01**	**0.02**	0.07	**0.02**	0.44	0.32	0.07	**0.01**	**0.02**	**0.03**
1 hr	r^2	**0.27**	0.02	***0.15***	**0.16**	**0.22**	**0.19**	< 0.001	0.02	< 0.001	0.05	**0.38**	**0.13**
	p	**0.00**	0.45	**0.02**	**0.02**	**0.00**	**0.01**	0.93	0.47	0.94	0.19	**< 0.001**	**0.04**
6 hr	r^2	**0.22**	< 0.001	0.02	0.07	**0.21**	0.06	**0.12**	0.02	0.00	0.01	***0.35***	0.04
	p	**0.01**	0.93	0.44	0.13	**0.01**	0.15	**0.05**	0.40	0.71	0.66	**< 0.001**	0.26

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test).

Table 6-4 i Linear Regression Results For Each Month – Pitt Polder

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.00	0.08	0.01	0.05	0.10	**0.18**	0.00	0.12	0.05	**0.22**	0.10	0.03
	p	0.73	0.10	0.63	0.25	0.08	**0.02**	0.71	0.05	0.25	**0.01**	0.07	0.33
15 min	r^2	< 0.001	0.01	0.01	0.00	0.08	0.09	0.01	0.02	0.00	**0.18**	0.10	0.08
	P	0.95	0.55	0.66	0.81	0.11	0.09	0.57	0.43	0.76	**0.02**	0.07	0.13
1 hr	r^2	0.00	0.06	0.04	0.01	**0.16**	0.08	0.00	0.03	0.00	0.06	0.02	0.04
	p	0.71	0.18	0.29	0.71	**0.03**	0.12	0.85	0.31	0.75	0.18	0.42	0.28
6 hr	r^2	0.01	0.11	0.00	< 0.001	**0.13**	< 0.001	0.00	0.01	0.03	< 0.001	0.01	0.04
	p	0.68	0.06	0.85	0.98	**0.05**	0.90	0.82	0.56	0.31	0.92	0.54	0.27

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test) (none).

Table 6-4 j Linear Regression Results For Each Month – Surrey-Kwantlen

Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.02	0.00	0.00	**0.18**	0.02	**0.17**	0.01	0.01	< 0.001	***0.17***	0.07	**0.18**
	p	0.39	0.84	0.76	**0.01**	0.43	**0.01**	0.65	0.62	0.92	**0.01**	0.13	**0.01**
15 min	r^2	< 0.001	0.00	0.04	**0.17**	0.04	**0.13**	0.00	0.00	0.01	**0.15**	0.01	0.09
	p	0.88	0.84	0.26	**0.02**	0.27	**0.03**	0.83	0.85	0.66	**0.02**	0.62	0.09
1 hr	r^2	0.01	0.01	0.02	0.05	***0.17***	0.09	0.00	< 0.001	< 0.001	0.05	0.01	0.00
	p	0.69	0.50	0.40	0.21	**0.02**	0.08	0.75	0.98	0.95	0.17	0.66	0.85
6 hr	r^2	0.03	0.11	***0.14***	0.01	0.05	0.06	< 0.001	0.00	0.01	0.00	0.03	0.00
	p	0.31	0.05	**0.03**	0.65	0.18	0.14	0.96	0.79	0.49	0.73	0.28	0.84

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test).

Table 6-4 k Linear Regression Results For Each Month – YVR

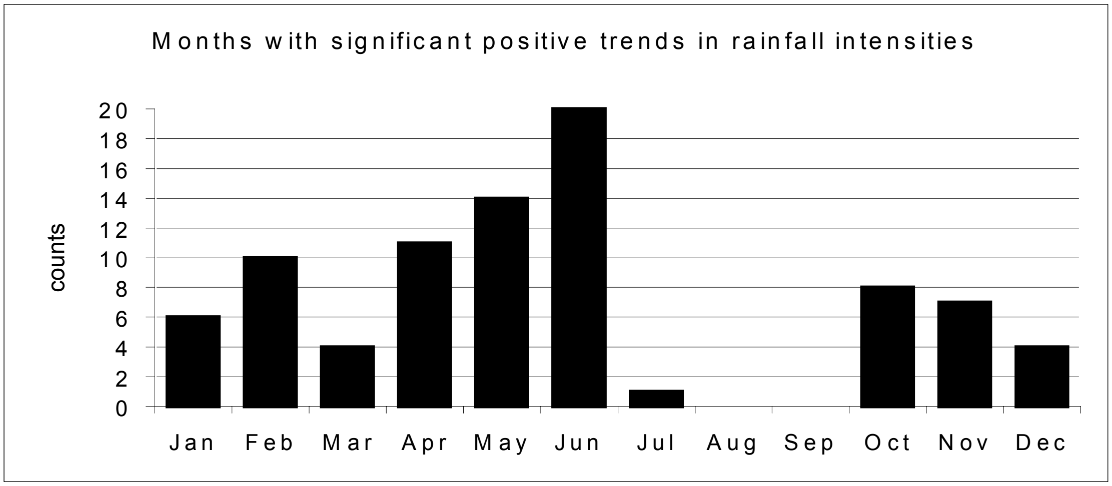
Dur.		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
5 min	r^2	0.00	0.03	0.01	**0.12**	0.10	**0.17**	0.07	< 0.001	0.03	0.01	0.02	0.17
	p	0.74	0.83	0.55	**0.04**	0.06	**0.01**	0.12	0.87	0.31	0.60	0.35	0.01
15 min	r^2	< 0.001	0.01	0.02	0.06	0.05	**0.15**	0.05	< 0.001	0.00	0.02	0.06	0.05
	p	0.96	0.62	0.40	0.15	0.18	**0.01**	0.17	0.89	0.73	0.43	0.13	0.16
1 hr	r^2	0.00	0.01	0.02	**0.11**	0.06	**0.18**	0.04	0.06	0.00	0.01	0.16	0.05
	p	0.90	0.62	0.39	**0.05**	0.13	**0.01**	0.21	0.16	0.79	0.51	0.01	0.16
6 hr	r^2	0.02	0.01	0.00	0.07	0.00	0.08	0.02	0.07	0.03	0.02	0.02	< 0.001
	p	0.43	0.54	0.73	0.11	0.79	0.09	0.38	0.12	0.29	0.45	0.41	0.87

Notes: Numbers in bold face are statistically significant at $p < 0.05$. Only number in italics are normally distributed (Shapiro-Wilk's W test) (none).

The linear regression analysis of monthly data allows the following conclusions:

- increases in precipitation intensities were found for all four rainfall durations;
- May and June show the most pervasive positive trends in precipitation intensities, followed by April, February, October, November, January, March and December (see Figure below);

Figure 6-1
Distribution of Months with Positive Trends in Rainfall Intensity



- the summer months July, August, and September show no increase in precipitation intensity for any duration;
- very few statistically significant regressions are normally distributed; and
- if trend projections be attempted, the data sets will have to be transformed and the new function be used in the predictive equations.

It is important to note that the dramatic change in counts of positive trends from June to July may be a consequence of the small precipitation amounts typically recorded in these months. Similarly, storms during these months are of short duration and will therefore have little impact on rainfall intensity durations in excess of one hour. Despite some statistical bias, it appears that April, May and June are the months of most significant positive trends.

Monthly time series are shown in Appendix B while the monthly linear regression results are summarized in Table 6.4 for durations of up to six hours. As expected for events that are likely convective in nature (and therefore associated with the movement of isolated precipitation “cells”) the results show relatively little spatial consistency overall. Statistically significant correlations (although with low r^2 and subtle upward slopes of the linear regression line) appear in a range of durations, across different times of year and different localities. However, when viewed in their entirety, these data do suggest a reasonably widespread and consistent weak upward trend in maximum monthly intensities across a broad range of stations during spring months (April, May, June). This pattern is apparent at North shore stations (DN25, VW14), Vancouver stations (VA14, VA01, VA13), surrounding suburban localities (QT10, BU13, Surrey Kwantlen, YVR) and as far afield as Pitt Polder.

The monthly time series (Appendix B) suggest that this upward spring trend has not been sustained over the entire period of record. At YVR for example, the June upward trend in 5 min. maximum intensity appears to begin in the late 1970s (coinciding with the well-documented 1977 switch in the PDO). The lack of a summer trend, and the spatially widespread nature of this spring pattern, suggest that it is not associated with local urban or topographic influences. It is more likely that the observed trend is circulation related and results from subtle changes in the stability of air masses reaching the west coast. As PDO and ENSO strongly influence offshore sea surface temperatures, it might be expected that these phenomena would influence the variability of extreme monthly precipitation in the Vancouver region however this aspect has not been adequately investigated to draw any firm conclusions regarding short duration rainfall. Given the cyclic nature of this effect (i.e. fluctuating with the PDO and ENSO), it would therefore be imprudent to project such trends into the future.

RAINGAUGE DATA FROM THE NORTH VANCOUVER DISTRICT HALL (STATION DN25)

The trend analyses for the GVRD and MSC stations have shown that there is a distinct discrepancy between station DN25 and all other stations. Only DN25 shows a pervasive and statistically significant upward trend for durations from 5 minutes to 2 hours (Table 6-1 and Appendix B-1B).

It was argued in previous subsections that the observed trend at DN25 may be due to the location of the raingauge near the cooling towers of the District building. A rational explanation would be that water vapour from the cooling tower condenses in a fine mist and falls in the tipping bucket raingauge, thus artificially increasing precipitation totals and intensities.

The cooling tower cools water from the “chiller” by evaporation. Large quantities of air are pumped against the flow of vaporized water that runs over the tower core. A primary and secondary fan further enhances evaporation. The fan cycle is dependent on ambient temperature, with greatest use of the secondary fan during the hottest time of the day of the hottest months. Water vapour exits at the top of the cooling tower when it is cycling. In addition to the cooling tower, there are two boiler stacks for natural gas fired boilers, which heat the Municipal Hall. The stacks pass combusted natural gas waste products. They run all year, but are on pilot only in the warmer months. The influence of the boiler stacks on precipitation measurement are unknown but are believed to be minor compared to the effect of the cooling tower. An experimental study would have to be conducted to quantify the exact impact of the cooling and heating system on the precipitation measurements. This experiment is recommended to adjust precipitation records since 1995 and make raingauge DN25 useable for future studies. Alternatively, DN25 should be moved.

This subsection provides a detailed analysis of the DN25 data to ascertain that the raingauge location is indeed biasing the measured results. This is very important because numerous hydrological and hydrotechnical studies are using data from this station. The underlying hypothesis is that the reconstruction of the District Hall in 1994/1995, which brought the raingauge to its present location 6 m north of the cooling tower outlet on the District Hall’s roof, has caused a significant increase in both precipitation totals and intensities.

Several avenues were chosen to prove that bias exists and to quantify the effect of the raingauge location. These are:

- detection of abrupt changes in the frequency distribution of precipitation intensities over time;
- comparison of means for monthly precipitation and maximum precipitation intensities before 1994 and after 1994 for DN25, VW14, and DN15; and

- comparison of means monthly precipitation and maximum precipitation intensities between the KWL raingauge and DN25 for the past 7 years.

Changes in Frequency Distributions

If there is a marked step change in precipitation totals and intensities associated with the relocation of the raingauge after reconstruction of the District Hall, it should be expected that the associated frequency distributions will also change abruptly at the time of construction. To test this hypothesis, the frequency distributions were plotted in 5-year intervals from 1965 to 1999 (Figure 6-3).

From this figure, it is evident that the distribution has shifted markedly to the right for the last data interval (1995-1999). This means that a higher percentage of precipitation falls at higher intensities than before 1995. If there was a gradual trend towards higher precipitation intensities, one would see a gradual shift of the frequency distribution towards the right, which is clearly not the case. Although not entirely conclusive since even an abrupt shift could be climate related, Figure 6-3 suggests that an abnormal increase in rainfall intensity has occurred over the 1995 to 1999 period.

Averaging precipitation for the four 5-year intervals before 1995 that have continuous data records, the mean precipitation volume is 995 mm, compared to 1,358 mm for the 1995 to 1999 period. This 37% difference suggests an artificial control. The following analyses will test whether this effect may in fact be due to climate forcing or is a residual of the instrument's location.

Comparisons of Means (DN25, VW14, DN15)

The previous subsection shows that an abrupt step change in rainfall intensity exists. If this change is real (i.e. climatically driven), it would likely occur in nearby stations. The closest stations are DN15 (Cleveland Dam) and VW14 (District Hall of West Vancouver).

The data were split in "before 1994" and "after 1995" sets. Figure 6-3 suggests that the means for DN25 should be significantly higher in the period after construction than before. If this effect is climatically caused, a similar increase in means should be expected for DN15 and VW14. Table 6-5 summarizes the findings from the analyses. Only 5 min, 15 min, 1 hour and 2 hours were chosen for the analysis because these durations show the most significant trends.

Table 6-5
Comparisons of Means Between DN25 and DN15 / VW14

	Total		5 min		15 min		1 hr		2 hr	
	DN25	**DN15**	**DN25**	**DN15**	**DN25**	**DN15**	**DN25**	**DN15**	**DN25**	**DN15**
Mean 1965-1979	148.9	176.7	16.2	20.4	11.4	13.3	6.8	7.7	5.1	5.9
Mean after 1995	174.6	178.9	22	20.2	15.3	14.6	8.2	8.5	6	6.4
% change	17.3	1.3	36.2	-0.8	33.5	9.6	20.6	11	17.4	7.3
	DN25	**VW14**	**DN25**	**VW14**	**DN25**	**VW14**	**DN25**	**VW14**	**DN25**	**VW14**
Mean 1965-1994	148.8	136.8	16.4	18.0	11.5	11.8	6.9	6.7	5.2	5.2
Mean after 1995	181.6	133.7	22.2	18.0	15.5	12.5	8.5	7	6.2	5.2
% change	22.1	-2.3	35.9	0.2	34.8	5.5	22.5	4.8	18.7	-1.1
The mean change at DN25 from 1965 - 1979 to 1995-2001 for 5 min, 15 min, 1 hr and 2 hrs is 26.9%. The mean change at DN 15 from 1965 - 1979 to 1995-2001 for 5 min, 15 min, 1 hr and 2 hrs is 6.8%. The mean change at DN25 from before 1994 and from 1995-2001 for is 28%. The mean change at VW14 from before 1994 and from 1995-2001 for 5 min, 15 min, 1 hr, 2 hrs is 2.3%.										

Table 6-5 draws a conclusive and coherent picture. The increase in means at DN25 from data records before 1994 to the period 1995-2001 range between 17% and 36%, while at DN15 and VW14 these changes range from -1% to a maximum of 11%. This analyses shows that the abrupt change in precipitation totals and intensities recorded at DN25 is not matched by neighbouring stations strongly suggesting that the bias is introduced by the location of the instrument. This is particularly apparent for the shorter durations. At higher durations this difference is lower because of a weaker trend for the 1 and 2 hours durations as recorded in Table 6-3 at DN25 and VW14.

Comparisons of Means between DN25 and the KWL Raingauge

As a final line of evidence data from DN25 and the KWL raingauge were compared for the past 7 years for which KWL has gathered data. KWL's raingauge is only approximately 1.5 km south of DN25 and is therefore the closest raingauge. Based on Figure 2-1 we would expect DN25 to have annual precipitation of about 5% more than KWL. DN25 is approximately 50 m higher than KWL's site. Since there are no major topographic constraints between the two sites, it is expected that KWL's data closely matches the data at DN25. Table 6-6 shows the comparisons of means for durations from 5 minutes to 24 hours.

Table 6-6
Comparison of Mean Precipitation Intensities at DN25 and the KWL Raingauge

	Total	5 min	10 min	15 min	30 min	1 hr	2 hrs	6 hrs	12 hrs	24 hrs
Mean (KWL)	155.6	23.3	17.4	14.7	10.7	7.5	5.4	3.5	2.4	1.9
% diff. To DN25	-14.3	4.7	-4.0	-5.2	-7.1	-11.3	-13.8	-16.2	-18	-20.8
The mean difference in precipitation intensities between DN25 and KWL raingauge is -10%.										

According to Table 6-6, precipitation totals are up to 21% higher at the DN25 than at the KWL raingauge with a mean of approximately 10%. Again, it seems that DN25 receives exaggerated amounts and intensities of rainfall compared to KWL's rain gauge than may be expected by its slightly higher elevation.

In summary, it is obvious that an abrupt change in precipitation totals and intensities has occurred at DN25 since 1995. The most rational explanation of this shift that cannot be observed at nearby stations, is the effect of the cooling tower which was installed at approximately the same time as the shift towards higher and more intensive precipitation occurs. As a consequence, trends based on the full data record are biased which demanded the removal of the last 6 years from further data analysis.

Despite this analysis, it is important to quantify the impact of the raingauge's location on the duration and intensity of rainfall. This can only be accomplished by setting up a raingauge in the vicinity of DN25, but unaffected by the cooling tower. The two gauges should be operating simultaneously for a period of at least two years. This would then allow a detailed quantification of the influence of temperature, wind speed and direction, and precipitation amounts and intensity on the hypothesized error in readings at DN25. A formula could then be devised that allows adjustment of DN25 data for the period since 1995.

6.3 CHANGES IN THE FREQUENCY OF HIGH INTENSITY RAINFALL EVENTS

Subsection 6.2 has so far focused on the highest precipitation amounts in each year or month. Equally important to long-term changes in the single highest events may be changes in the second, third and nth highest rainfall intensities. For example, a given precipitation intensity threshold may be exceeded more and more frequently over time without being the record for a given month of year. The previous analysis would not be able to record this change. For this reason, this section presents a detailed analysis of changes in the frequency of high rainfall intensity events.

To process the data efficiently, the program "EXCEEDCOUNT" was written in the advanced data analysis programming language PV-WAVE (by Visual Numerics Inc). The program performs the following steps:

- The program is capable of handling approximately 1 decade of data at a time (approximately 1 million data points at 5-minute resolution). This is a limitation on computer memory only and it could handle larger files with additional memory. Accordingly, GVRD 6-month data files were appended together into decade-long files prior to running the program.
- The program takes 5-minute rainfall data and develops different duration (5 min., 10 min., 15 min., 30 min., 1 hour, 2 hour, 6 hour, 12 hour and 24 hour) time series at 5-minute resolution. The time series are developed in terms of mm/hr of rain.

- For each duration, the program analyzes each 5-minute time step to determine if the rainfall has crossed the set threshold value for that duration. An integer flag array is used to keep track of every time the threshold value is crossed. The algorithm makes no attempt to define individual storm events. It may therefore report multiple threshold exceedances during the same storm event.

- After the entire signal for each duration has been scanned for threshold crossings, the program summarizes the number of times this occurs by year and month. The resultant output lists, for each year and month, the number of times the threshold value was exceeded for each of the given durations.

  The program EXCEEDCOUNT was used for the analysis of threshold exceedances as well as the SOI-ENSO correlation analysis.

PREVIOUS ANALYSIS

Similar analysis as the one conducted herein has been carried out by Reg Dunkley, Forensic Meteorologist at the Meteorological Survey of Canada in 1997. He analysed the number of days at which a common threshold of 10 mm/hr was exceeded for different durations. His analysis included Vancouver International Airport (YVR), Victoria International Airport, Abbotsford Airport and Comox Airport. Dunkley's conclusions were:

- At YVR, all durations analysed show a substantial increase in threshold exceedances was noted for the decade ending in 1976 compared to the decade ending in 1996.

- At YVR the observed trend continued for the 15 min and 30 min durations until 1996 with number of threshold exceedances doubling for the decade ending in 1996 compared to the decade ending in 1976.

- At Victoria, Abbotsford and Comox airports a peak was observed in early 1980.

- None of Victoria, Abbotsford or Comox airports showed the increasing trend in the late 1980s not the plateau in the 1990s that was recorded at YVR.

Given these observations, Dunkley concluded that the increased frequency of intense precipitation observed near Vancouver is localized and may be associated with impacts of urbanization and development, which are greater in the GVRD than the other study sites. He concludes that it is unclear whether climate change has any impact on the observed trends at YVR.

CHANGES IN THRESHOLD EXCEEDANCE

Common threshold exceedances were computed for all stations and all durations. Thresholds were visually determined for each durations. The underlying criterion for selection of the threshold was that sufficient data would exceed the threshold for the specific duration. For example, if the same threshold was used for each duration, then there would be either too many data (and thus excessive data noise) for the shorter durations, or there would be little or no exceedances for the longer durations making the interpretation of the data impossible. For this reason, the following thresholds were chosen:

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

Appendix B includes all threshold exceedance figures that are being discussed in this subsection.

Table 6-7 a-g lists qualitative and quantitative observations on the number of threshold exceedances for all analysed GVRD and MSC stations. The quantification is based on linear regression analysis.

Table 6-7 a Threshold Exceedance Analysis for DN25 (1964-1994)

Durations	**Qualitative Description**	**R^2**	**p**
5 min	Extremes in 81, 92, increasing trend	0.06	0.305
10 min	Extremes in 81, 92, increasing trend	0.00	0.417
15 min	Extremes in 81, increasing trend	0.04	0.496
30 min	Extremes in 81, increasing trend	0.01	0.114
1 hr	Extremes in 81 increasing trend	0.00	0.870
2 hrs	Increasing trend	0.00	0.934
6 hrs	No extremes, increasing trend	0.00	0.890
12 hrs	Extreme in 81, increasing trend	0.00	0.665
24 hrs	Increasing trend	0.00	0.646
Note: Data from 1995 on are questionable (see previous subsection).			

Table 6-7 b Threshold Exceedance Analysis for QT10 (1959-2001)

Durations	**Qualitative Description**	**R^2**	**p**
5 min	Extreme in 1991, no trend	0.04	0.212
10 min	Extreme in 1991, no trend	0.03	0.310
15 min	Extreme in 1981, no trend	0.01	0.648
30 min	Increasing trend	**0.11**	**0.033**
1 hr	No trend	0.01	0.613
2 hrs	No trend	0.01	0.580
6 hrs	Extreme in 1975, no trend	0.01	0.547
12 hrs	No trend	0.00	0.663
24 hrs	Extreme in 1998, no trend	0.00	0.778

Table 6-7 c Threshold Exceedance Analysis for VA04 (1960-2001)

Durations	Qualitative Description	R^2	p
5 min	Extremes in 1997, 1998, slight positive trend	**0.17**	**0.030**
10 min	Extremes in 1997, 2001, no trend	0.13	0.064
15 min	Extremes in 1960, 1997, no trend	0.10	0.093
30 min	Extremes in 1960, 1998, no trend	**0.18**	**0.025**
1 hr	No trend	0.00	0.978
2 hrs	Extreme in 2000, no trend	0.04	0.319
6 hrs	Extreme in 1997, no trend	0.00	0.771
12 hrs	Extreme in 1990, no trend	0.00	0.991
24 hrs	Extreme in 1997, no trend	0.06	0.220
Note: Data missing between 1974 and 1987 and 1999.			

Table 6-7 d Threshold Exceedance Analysis for VA01 (1959-2001)

Durations	Qualitative Description	R^2	p
5 min	Extremes in 97, 96, 98, 00, positive trend	**0.21**	**0.009**
10 min	Extreme in 97, positive trend	**0.17**	**0.017**
15 min	Extreme in 90, 97, positive trend	**0.18**	**0.016**
30 min	Extreme in 97, positive trend	**0.27**	**0.003**
1 hr	Extremes in 96, 97, 99, positive trend	**0.23**	**0.005**
2 hrs	Extreme in 99, higher positive trend	**0.17**	**0.020**
6 hrs	Extreme in 71, no trend	0.01	0.528
12 hrs	No end	0.00	0.998
24 hrs	Extreme in 98, no trend	0.00	0.852
Note: Data missing between 1976 and 1987.			

6-7 e Threshold Exceedance Analysis for CW09 (1980-2001)

Durations	Qualitative Description	R^2	p
5 min	Extreme in 86, declining trend	**0.40**	**0.001**
10 min	Extreme in 81, declining trend	**0.29**	**0.009**
15 min	Extreme in 86, no trend	0.11	0.138
30 min	Extreme in 96, increasing trend	0.00	0.993
1 hr	Extreme in 80, declining trend	0.10	0.077
2 hrs	Extreme in 80, no trend	0.08	0.211
6 hrs	No trend	0.00	0.846
12 hrs	No trend	0.05	0.313
24 hrs	Extreme in 86, no trend	0.00	0.764

6-7 f Threshold Exceedance Analysis for VA13 (1950-2001)

Durations	Qualitative Description	R^2	p
5 min	Extreme 97, increasing trend	**0.48**	**0.000**
10 min	Extreme 97, increasing trend	**0.48**	**0.000**
15 min	Extreme 97, increasing trend	**0.40**	**0.000**
30 min	Extremes 97, 91, 98, 99, increasing trend	**0.33**	**0.000**
1 hr	Extremes 97, 98 increasing trend	**0.39**	**0.000**
2 hrs	Extremes 68, 91, 97, 98 increasing trend	**0.24**	**0.017**
6 hrs	Extremes 90, 97, 98 increasing trend	**0.43**	**0.000**
12 hrs	Extremes, 90, 97 increasing trend	**0.35**	**0.000**
24 hrs	Extremes, 97, 54, 90, 91 increasing trend	**0.17**	**0.010**
Note: Data missing from 1974 to 1987.			

6-7 g Threshold Exceedance Analysis for BU31 (1951-1974)

Durations	Qualitative Description	R^2	p
5 min	Extremes 97, 95 increasing trend	**0.50**	**0.000**
10 min	Extremes 97, 95, 94 increasing trend	**0.61**	**0.000**
15 min	Extremes 97, 95 increasing trend	**0.57**	**0.000**
30 min	Extremes 97, 95, 93 increasing trend	**0.54**	**0.000**
1 hr	Extremes 95, 96 increasing trend	**0.56**	**0.000**
2 hrs	Extremes 90, 95, 97 increasing trend	**0.52**	**0.000**
6 hrs	Extremes 90, 95, 97 increasing trend	**0.58**	**0.000**
12 hrs	Extremes 90, 95, 97 increasing trend	**0.43**	**0.000**
24 hrs	Extremes 96, 92, 97 increasing trend	**0.45**	**0.000**

Note: Data between 1974 to 1988 missing.

6-7 h Threshold Exceedance Analysis for Surrey-Kwantlen (MSC)

Durations	Qualitative Description	R^2	p
5 min	Extreme, 89 increasing trend	**0.02**	**0.005**
10 min	Extreme, 97 no trend	0.00	0.382
15 min	Extreme, 97 no trend	0.00	0.718
30 min	Extreme, 97 increasing trend	**0.01**	**0.023**
1 hr	Extreme, 97 increasing trend	0.01	0.089
2 hrs	Extremes, 81, 97 increasing trend	**0.01**	**0.020**
6 hrs	Extreme 75, no trend	0.00	0.543
12 hrs	Extreme 83, no trend	0.00	0.510
24 hrs	No trend	0.00	0.268

6-7 i Threshold Exceedance Analysis for Vancouver Airport (MSC) (1960-1999)

Durations	Qualitative Description	R^2	p
5 min	Extremes 81, 89, 97, slight upward trend	**0.03**	**0.000**
10 min	Extreme 80, 88, slight upward trend	**0.01**	**0.024**
15 min	Extreme 81, slight upward trend	**0.01**	**0.008**
30 min	Extreme 68, no trend	**0.01**	**0.039**
1 hr	Extreme 81, 97, slight upward trend	**0.02**	**0.002**
2 hrs	Extreme, 96, 97	**0.02**	**0.007**
6 hrs	Extreme 81, 97, slight upward trend	0.00	0.130
12 hrs	Extreme 83, no trend	0.00	0.131
24 hrs	Extreme 75, no trend	0.00	0.415

When evaluating the results for each station, it is important to compare only R^2 values, p values, and general patterns as seen on the graphs in Appendix B. Total exceedance counts cannot be compared between stations that have data missing at different times, nor can they be compared between GVRD and MSC stations. GVRD stations provided data at a 5-minute frequency, which implies that the rain intensity threshold could be exceeded more than once in a day. MSC data is available as a daily maximum intensity, which means that though the threshold may have been exceeded several times in a day, only the maximum daily intensity is available to be counted. As a result, one could expect more threshold exceedances for the GVRD stations. Because this study looks at trends for individual stations, this data difference between GVRD and MSC stations does not affect the results.

MONTHLY ANALYSIS

The data were stratified by month to investigate whether there are any systematic changes in threshold exceedance frequency for certain months as observed for the spring months in Section 6.

Only four stations proved to be suitable for this analysis because of data discontinuity. These are station DN25 (record biased after 1994), station QT10, YVR and Surrey (Appendix B).

Station DN 25 shows an increase in exceedance counts for the months of January (5 min and 15 minute durations), June (5 min, 15 min, 1 hr), October (5 min, 15 min, 1 hr) and November (5 min, 15 min, 1 hr). Station QT 10 shows a slight increase in exceedance counts for April (5 min, 15 min).

SUMMARY

The data analysed herein gives rise to three important observations:

- In the 1990s there has been a significant increase in number of exceedances of 10 mm/hr rainfall events. However, statistical analysis is hampered by discontinuous data records. Furthermore data at DN25 are likely biased and cannot be used for this interpretation. Despite these limitations, a general positive trend in threshold exceedances can be discerned at a number of stations.
- The observed increase cannot be observed in all stations.
- The year 1997 witnessed by far the highest occurrence of threshold exceedances. The winter of 1997/98 has also been the strongest El Niño on record. However, there is no proof available that El Niños are responsible for higher precipitation intensities in the GVRD and the higher occurrence could have occurred early in 1997, before the El Niño developed.

Because the record length of this analysis is only 50 years at best, the following subsection will investigate whether the observed trend may be due to a changing climate or whether it is part of a natural cyclicity, or a function of both.

6.4 ANALYSIS OF THRESHOLD EXCEEDANCE CYCLICITY

The above analysis has demonstrated that there is a trend in the exceedance of rainfall intensity thresholds observed within the GVRD but the robustness of the analysis is impeded by discontinuous data series. The following analysis focuses on explaining the variability observed in the threshold exceedance data.

Two variables are being used to explain the data variability, the ENSO index and PDO index. The derivation of these indices is explained in Appendix A and F. The goal of this analysis is to find any correlations with either ENSO or PDO to predict threshold exceedances. If no correlation is found the data would suggest that neither ENSO nor PDO influences the temporal distribution of extreme rainfall events, and that the observed distributions are likely not driven by either ENSO or PDO cycles.

To complete this analysis, the exceedance data, SOI and ENSO data were normalized to obtain comparable value magnitudes and plot it on the same y-axis (Figures B-1F to B-11F, Appendix B). Standardization is accomplished by subtracting the mean of the distribution and then dividing it by its standard deviation.

VISUAL INSPECTION

Before starting quantitative analyses, it is often important to examine the data visually. For this purpose the PDO, ENSO and exceedance data were standardized and plotted on a common graph. (See Appendix B, Chart B-3F). There are four relevant observations that can be made from this cursory inspection:

- The Southern Oscillation Index and the Pacific Decadal Oscillation behave roughly opposite (i.e. negative SOI is usually associated with positive PDO and vice versa). (By convention, a negative SOI signifies a warm ENSO event and a positive PDO signifies a warm event in the North Pacific.)

- At around 1978 (which coincides with a shift from a PDO cool phase to a PDO warm phase), the SOI is more often negative indicating more frequent warm ENSO conditions, while the PDO is mostly positive indicating overall warmer conditions over the central and northeastern Pacific Ocean and thus in coastal B.C.

- Since 1978, the amplitude of threshold exceedances has increased dramatically.

- The two most significant periods of threshold exceedances coincide with the two most intensive El Niños of the 20th century for rainfall intensity durations up to 1 hour.

COMPARISON OF MEANS

Mean exceedance counts were computed for the pre-1977 period (based on a maximum of 20 years before 1977) and the post 1977 period (until 1998). This comparison serves to identify any significant changes from the last PDO cool cycle to the last PDO warm cycle. Table 6-8 provides the individual means for all stations with sufficient records.

Table 6-8
Changes in Mean Exceedance Counts from Pre-1977 to 1998

	VA04	VA13	VA01	QT10	BU31	YVR	Surrey
Δx (%)	31	91	49	14	176	57	28

Δx is the average change in mean exceedance counts from the pre-1977 to the post 1977 period.

In summary, the comparison of mean exceedances between the pre-1977 period and the post 1977 period shows a statistically significant average increase of 64% with a range from 14% (QT10) to 176% (BU31). Data are often continuous and the lengths of records are variable. Because some data is missing in the middle of the record, data are leveraged towards the beginning and end of the record decreasing the robustness of the statistical methods used. For this reason, the percentages provided in Table 6-8 are associated with some error, which can only be deleted if the entire data record were available. Despite these statistical hindrances, a significant increase in threshold exceedances can be observed after 1977, suggesting that PDO warm phases are associated with more frequent high intensity precipitation events.

MULTIPLE REGRESSION ANALYSIS

Multiple regression analysis was performed for several stations using SOI and PDO as the dependent variables. The objective of this analysis was to investigate whether a combination of SOI and PDO indices could explain observed variance of threshold exceedances. Multiple regression analysis uses the same techniques as simple linear regression analysis, but incorporates two or more dependent variables.

Multiple regression analysis was performed for all stations and all durations. It was found that there are several weak relationships between rainfall exceedance counts and PDO. Variances explained ranged as high as 14% with most variances being significantly lower. This analysis shows that the PDO and SOI indices are inadequate to use in a predictive model for high intensity rainfall exceedances. However, it strengthens the conclusions drawn from the visual inspection and comparison of means that PDO cycles influence the temporal distribution of high intensity rainfall.

Section 7

Summary and Recommendations

7. SUMMARY AND RECOMMENDATIONS

This final section provides a short summary of the key findings of this report and recommends further action with regard to climate-related studies for the GVRD.

7.1 SUMMARY

The summary is structured by the main point of the literature review and the principal conclusions from this study as follows:

LITERATURE REVIEW CONCLUSIONS

1. Average temperature has changed significantly over the past few hundred years. The Little Ice Age temperatures were about 1°C lower than in the 20th century.

2. The current consensus in the scientific literature is precipitation will likely increase by approximately 10% in coastal areas of B.C. and significantly higher in the interior of B.C. over the next century. Total annual precipitation has increased over the past century by less than 10 % in coastal British Columbia. In the Interior, precipitation increases have been substantially higher.

3. The mean precipitation of the period reconstructed by dendrochronology (1670 – 1900) does not differ from the mean of the instrumental record (1900 to present), implying that to date there is no pervasive trend in the long-term precipitation pattern in the Pacific Northwest and southwestern B.C.

4. The Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) dominate variations in the precipitation and temperature regime in southwestern British Columbia and will likely continue to do so. A shift towards quasi-permanent El Niño conditions is possible as the central Pacific continues to warm but only over a long period of time.

5. There is some evidence that the frequency of deeper-than-average air pressure lows in the North Pacific has increased by approximately 50% and central pressures in cyclones have decreased by 4-5 hPa (mb).

STUDY CONCLUSIONS – STREAMFLOW AND SNOWPACK

6. Streamflow records from North Shore rivers and creeks do not show any long-term trends towards wetter conditions in the future. There is a weak correlation between PDO and streamflow in some rivers but other factors are likely to obscure the signal.

7. Precipitation intensity and stream discharge are poorly correlated at Mackay Creek. This is largely due to the buffer of vegetation, soil and snow which will significantly

diffuse a precipitation intensity signal, particularly for short durations. Correlations for larger gauged natural streams were not attempted because larger watersheds are unlikely to respond to changes in precipitation intensities. Better correlations may be found between very small urban watersheds that were not included in this study.

8. Snow water equivalent at Grouse Mountain is not correlated with precipitation intensity. However, it seems to be strongly controlled by PDO cycles and ENSO. There is little correlation between snow water equivalent and maximum daily or mean daily stream discharge. PDO and ENSO controlled snowwater quantities have little implications for the GVRD's stormwater and sewer infrastructure, but are very important for the prediction of water availability for the GVRD's water system.

STUDY CONCLUSIONS – RAINFALL INTENSITIES

9. There is some evidence for a modest increase in short-duration summer precipitation intensities in the GVRD in the past 10 years. This pattern is most likely attributable to the impacts of PDO and ENSO. Urbanisation effects may also be a contributing factor but further analysis is needed to confirm this assertion.

10. There is little evidence that precipitation intensities have increased systematically over the period of record (approximately 40 years) for all GVRD stations except DN25 (District Hall of North Vancouver), whose data is suspect in latter years and VW 14 (District Hall of West Vancouver). At DN25, it was found that the raingauge receives excess water from condensation due to its location near the cooling tower of the District Hall. After removing the data from the year at which the building was reconstructed and the cooling towers installed (1994), statistically significant linear regressions can only be found for the 1 and 2 hour rainfall durations. No significant trends in precipitation intensities were found for the three MSC stations analysed.

11. A month-by-month analysis of May and June show the most pervasive positive trends in precipitation intensities, followed by April, February, October, November, January, March and December. No trends were found for July, August and September.

12. In the 1990s there has been a significant increase in number of exceedances of 10 mm/hr rainfall events. The 1990s have also been the warmest decade in the last millennium globally.

13. The year 1997 shows the most frequent threshold exceedances. The winter of 1997/98 was also the strongest El Niño on record. It is not known whether this is a coincidence.

14. An analysis of the cyclicity of high intensity rainfall exceedances demonstrates a significant increase in 10 mm/hr exceedances from the pre-1977 to the post 1977 period which coincides with the last cycle shift from a PDO cool phase to a PDO warm phase.

15. Multiple regression analysis does not allow reliable forecasting of threshold exceedances given PDO and SOI parameters, but suggests that PDO influences high intensity rainfall threshold exceedances.

STUDY CONCLUSIONS – TENTATIVE FORECAST

16. There is increasing evidence that a PDO cool phase has been entered in 1998. If this occurs, it implies depressed rainfall intensities (particularly in the spring months) for the duration of this cool phase (next 20 years or so). Equally, threshold exceedances are likely to be lower during the current PDO cool phase. Therefore, less stress on the GVRD's drainage and sewerage system might be expected for the next 20 years.

17. Despite generally lower rainfall intensities and fewer occurrences of 10 mm/hr intensity rainfall, strong year-to-year variability can be expected due to ENSO and other cycles as well as random variability.

18. Snowdepth and snow-water equivalents are likely to be higher during the current PDO cool phase as compared to the last warm phase (1977-1998).

19. Continued global warming and enhanced hydrological cycle may alter the historical relationship in which the PDO cool phase has less 10 mm/hr exceedances.

7.2 RECOMMENDATIONS

Several key recommendations can be made. These are structured by operational recommendations and management recommendations.

OPERATIONAL RECOMMENDATIONS

1. It is necessary that all GVRD raingauges be assessed by a meteorologist knowledgeable in data collection and instrument exposure. Data should be corrected for windspeed and other possible confounding factors. In some instances, raingauges may be relocated.

2. Every effort should be made to ensure that data is recorded continuously and that malfunctioning raingauges be repaired as soon as possible to avoid excessive data gaps as encountered in this study.

3. A controlled experiment should be conducted with a second raingauge at the District of North Vancouver raingauge DN25 to adjust data since 1994. After having completed this experiment, the present raingauge should be dismantled in favour of a nearby calibrated raingauge.

4. All strip chart data should be digitized. As this is complete sections of this analysis should be updated.

5. This analysis should be updated approximately at five-year intervals to detect any sudden unexpected changes in rainfall intensities.

MANAGEMENT RECOMMENDATIONS

6. There is no urgent need for installation of higher capacity sewer and drainage systems anywhere in the GVRD based on precipitation intensity trend analyses.

7. There is evidence that mean annual precipitation will increase by approximately 10% over the next century in southwestern British Columbia. It is therefore prudent to upgrade existing stormwater sewers, combined sewers and drainage systems to higher capacities as part of the regular maintenance cycle.

8. Given the results from this study it appears unnecessary to advance to a Phase III study as outlined in the GVRD's original request for proposal. Rather, it is recommended that a limited Phase II study of climate change scenarios be carried out that summarizes current climate modelling efforts with respect to changes in total precipitation.

9. The findings of this report should be made available to other sections of the GVRD, particularly the reservoir operations because of significant findings relating to the control of PDO and ENSO to snow water equivalent.

10. A separate study is recommended to develop a multivariate statistical model to provide predictions of snowwater equivalents and snowdepth with a 6 months lead-time. A range of experimental ENSO models should be used as input to the model to ensure broad representation from the scientific community.

7.3 REPORT SUBMISSION

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