Water Quantity and Quality in the Columbia Basin Trust Region

Water Resources Partnership between the Columbia Basin Trust and The University of British Columbia, Okanagan

Janice Brahney
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a place of mind

THE UNIVERSITY OF BRITISH COLUMBIA

Executive Summary

This report collects the documents generated as part of a two year effort to catalogue the variety of water quality and quantity data that has been collected in the Columbia Basin Trust region of British Columbia. Through the cataloguing effort, a number of important data and knowledge gaps were identified and specific recommendations developed. The available water quantity and climate data was then used in a number of analyses focused on understanding the relationship between changing climate conditions and stream discharges.

One overall finding is that there is a large variety of data collected and held by various different entities. These data sets exist in a variety of sometimes inconsistent formats, with different and sometimes challenging means of access. A unifying recommendation is that the Columbia Basin Trust, alone or in cooperation with other agencies, work to develop a data repository to collect and archive data sets and link to other data sources, and a portal to provide easy access for researchers and the public to this data.

The first two sections of the report catalogue the different data types and sources available. Water quantity data is described within the categories of climate, snow and glaciers, streams and rivers, lakes and reservoirs, and groundwater. Substantial gaps exist in the coverage of monitoring across the categories, particularly in more remote areas and higher elevations. Water quality data is less complete than the quantity data. Many water quality measures require some level of technical skill to collect, rendering the coverage even less complete than for the water quantity data. Expanding the network of water quantity measurement stations, increasing the number of people trained to collect water quality samples, and supporting them to do so, are recommendations that follow from inventorying the water quality and quantity data.

The next sections provide a more detailed overview of the data, with a particular emphasis on the observed and potential impacts of climate change. Based on the available data, temperatures in the Columbia Basin Trust area have increased by more than a degree Celsius in the last 100 years. This has coincided with a shift in precipitation towards more rain and less snow. However, there is insufficient data to accurately understand and estimate the effects at higher elevations, to measure evaporation, and to detect short term, intense weather events.

The dams built as part of the Columbia River Treaty have substantially changed the local ecology, flooding important riparian habitats and highly productive low elevation land areas, as well as displacing human settlements. There is limited data available to develop a comprehensive understanding of the changes that building the treaty dams have had on water quality and aquatic ecology. Beyond the impoundments, there is almost no information on the natural aquatic habitats in the region, particularly in the headwater regions where changes can have cascading ecological effects downstream. Going forward, continuing and expanding monitoring efforts and data warehousing will be necessary to monitor the continuing evolution of the system, and to detect and as appropriate mitigate the effects of a changing climate.

The existing stream discharge data were analyzed to detect trends, and relate these trends to large scale climate changes. Consistent with other studies conducted in the American northern Rocky Mountains, the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) are important predictors of discharge levels. The measured impacts differed somewhat across the basin, broadly exhibiting the same general trends. However, the northeast region, an area with more high elevation areas and greater glaciation, was inconsistent with the findings from the other regions. This again highlights the importance of extending monitoring into the higher elevation areas of the basin. As found elsewhere, there is evidence that the relationship between climate variables and discharge has changed in recent times. Model results suggest that discharges are trending differently from the generally accepted projections. Given the important role that water yield from the Canadian portion of the Columbia River plays in this international river basin, increased monitoring and further analysis is recommended.

Snow accumulation and glaciers are important contributors to the timing and volume of stream discharge in the basin. Monitoring of the snowpack is reasonably well covered at lower elevations. However, beyond 2000 meters above mean sea level monitoring is spotty. Snowfall at these elevations is important for glacial accumulation, measurement of which is necessary if we are to predict the future contributions of glaciers to discharge. Data on glacial mass is almost completely absent. Inferences made from observed late season stream discharges suggest that for many streams in the Columbia Basin Trust area, the contributions of glacial melt to stream flow has peaked and is declining. Expanding the high elevation snowpack monitoring and conducting more detailed investigations into the changes in glacial mass and behavior will help to more accurately forecast changes in stream discharge.

Groundwater resources in the basin are poorly understood. There are five groundwater monitoring wells in the basin. The valley fills are due to repeated glaciations, resulting in a complex pattern of aquifers. Little detail is known about these aquifers, their sources, and their potential yields. Beyond direct human use, groundwater also plays an important role in sustaining late season stream flows, particularly in lower elevation areas that do not have year round snow. Groundwater contributions also play a role in regulating water temperatures, which can be important for fish survival, particularly during the warmer parts of the summer. The ecological role of groundwater may increase with climate change. However, it is uncertain whether climate change will increase or reduce recharge rates, and consequently how groundwater yields will change. Better monitoring and more detailed modeling of groundwater resources will be important for better managing this resource and the impacts of climate change.

The catalogued data has permitted a few specific analyses to be conducted. However, there are a number of areas where data is almost completely absent. Some specific areas where data is limited include: wet and dry deposition of atmospheric contaminants around the basin, water quality impacts of the transition in the source of stream water from snow and glacial melt towards rain, monitoring and assessing the impacts of invasive species, and the sources and levels of pharmaceuticals and other introduced compounds. There has also been little effort to understand the cumulative effects of all the changes that are taking place throughout the basin.

As much as there are gaps in the data collected, and in the accessibility of these data to researchers and the general public, there is also a lack of sustained capacity to interpret these data and recommend management options. Data is not knowledge, and simply addressing the data gaps does not address the knowledge gaps. The final recommendation is to make a sustained commitment to building capacity within the basin, both through educating basin residents and in particular recruiting and retaining expertise that is committed to the region. This capacity is the critical link in translating data into knowledge, and investing in this capacity building should not be overlooked.

Project co-supervisor, Dr. John Janmaat
Associate Professor of Economics and
RIC Chair in Water Resources and Ecosystem Sustainability
I.K. Barber School of Arts and Sciences
The University of British Columbia

Table of Contents

Executive Summary i
Introduction 1
Acknowledgements 3
Section 1 Water Quantity Data Inventory 4
Introduction 4
1.0 Water Quantity Data Types and Sources 5
1.1 Climate Data 5
1.2 Cryosphere - Snow and Climate 7
1.3 Cryosphere – Glacier and Permafrost Data 8
1.4 Stream and River Data 9
2.4 Lake and Reservoir Data 10
1.6 Groundwater Data 11
1.7 Mapping Tools and Other Resources 12
References Section 1 13
Section 2 Water Quality Data Inventory 14
Introduction 14
2.0 Sources of Water Quality Data 14
2.1 Environment Canada: Fresh Water Quality Monitoring 14
2.2 Ministry of Environment: Environment Protection Division 15
2.3 GEMS: Global Environment Monitoring System 15
2.4 CABIN: Canadian Aquatic Biomonitoring Network 16
2.5 IHA: Interior Health Authority 16
2.6 DFO: Department of Fisheries and Oceans 17
2.7 BC Fisheries 17
2.8 Citizen science groups 18
References Section 2 19
Part 3 Data Analyses 20
Water in the Columbia 20
Water Quantity 20
Water Quality 21
Analyses Overview 22
3.1 Climate Change and the Hydrologic Cycle 24
3.1.1 Climate Indices 24

Uncertainties..25
Recommendations..26
3.1.2 Greenhouse Gas-induced Warming and Climate and Hydrologic Model Projections.....................26
Uncertainties..28
3.2 Catchment Disturbances..29
Knowledge Gaps 30
Recommendations..30
3.3 Historical Climate Changes in the Columbia Basin of Canada 31
Data Availability and Coverage 31
3.3.1 Data Analyses...33
Discussion 53
3.3.2 Summary of Data and Knowledge Gaps 54
3.3.3 Recommendations..55
4.0 Surface Waters...57
4.1 Lakes and Reservoirs..57
Data availability and coverage..57
4.1.1 Impoundments and channel modifications..58
4.1.2 Data and Knowledge gaps 60
4.1.3 Recommendations..60
4.2 Streams and Rivers 62
Water Quantity Data Availability and Coverage...62
Water Quality Data Availability and Coverage 63
4.2.1 Data Analyses...66
Discussion 121
4.2.2 Summary of Data and Knowledge Gaps 123
4.2.3 Recommendations...124
5.0 Cryosphere: Snowpack, Glaciers, and Permafrost...128
5.1 Data Availability and Coverage 128
5.2 Data Analyses...131
Discussion 137
5.3 Summary of Data and Knowledge Gaps 138
5.4 Recommendations...139~~138~~
6.0 Groundwater..140
6.1 Data Availability and Coverage 140
Groundwater in the CBTR 141

Groundwater in the Upper Columbia Region 143
6.3 Climate Change Impacts 144
6.4 Summary of Data and Knowledge Gaps 145
6.5 Recommendations 145
7.0 Major Assessment Gaps 147
7.1 Atmospheric Contaminants 147
7.1.1 Wet deposition 147
7.1.2 Dry deposition 148
7.2 Water quality effects of the melting cryosphere 148
7.3 Invasive or Bloom forming Species 149
7.4 Cumulative Effects Monitoring 150
7.5 Pharmaceuticals, Pesticides, and other Organic Contaminants 150
7.6 Summary of Data and Knowledge Gaps 150
7.7 Recommendations 151
8.0 Overarching Gaps and Recommendations 152
8.1 Data Access 152
8.2 Data Gaps 152
8.3 Data does not equate to Knowledge 154
8.4 Overarching Recommendations 155
Glossary and Abbreviations 157
References 158
Appendix 166

Introduction

The Water Science Research Partnership is a collaborative effort between researchers at the University of British Columbia, Okanagan (UBCO), and the Columbia Basin Trust (CBT). The primary goal of the Water Science Research Partnership is to gain a greater understanding of the state of both water quantity and quality in the Columbia Basin Trust Region (CBTR) (Figure 1). Though there are a variety of entities collecting water quantity and quality data within the CBTR, at present there is no single coordinating body and little understanding of the overall state of water quality in the basin, including historical conditions, present conditions, major stressors, and future outlooks. To better support water resource initiatives in the basin, CBT initiated a partnership with UBCO to produce scientifically defensible analyses of water resources in the CBTR.

The main objectives were to:

1. **Create an inventory of water quantity and quality data available for the CBTR.**
2. **Analyze existing data and identify knowledge gaps to develop a regional picture of water quality and quantity.**
3. **Provide recommendations to CBT and other organizations for their potential roles in water quality and quantity initiatives and future endeavours.**

This document is divided into two sections, Section 1 focuses on water quantity, and Section 2 on water quality. In each section, Part 1 includes a data inventory on water metrics, which includes the types of data collected, the organization collecting the data, and where and how the data is collected. Included as appendices are spreadsheets that contain site metadata. In each section Part 2 consists of an overview of data coverage and adequacy, statistical analyses, and identifies data and knowledge gaps. At the end of each water resource section, a synthesis of the results and recommendations to fill existing gaps are provided. The recommendations are not strictly for CBT but for any organization to consider in order to address the identified gaps.

The project builds on previous work carried out by various authorities within the Columbia Basin and was carried out by Dr. Janice Brahney at UBCO and guided by two faculty members, Dr. Jeff Curtis and Dr. John Janmaat, and an advisory committee of 10 members representing 9 organizations and institutions. These are

- Dr. Hans Schreier, UBC Emeritus
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- Dr. Brian Menounos, UNBC
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- Andrea Ryan, Environment Canada
- Lean Gaber, BC Ministry of Environment
- Russell White, Water Survey of Canada
- Katie Burles, Columbia Basin Watershed Network

- Ryan Macdonald, Hydrologist, Lotic Environmental

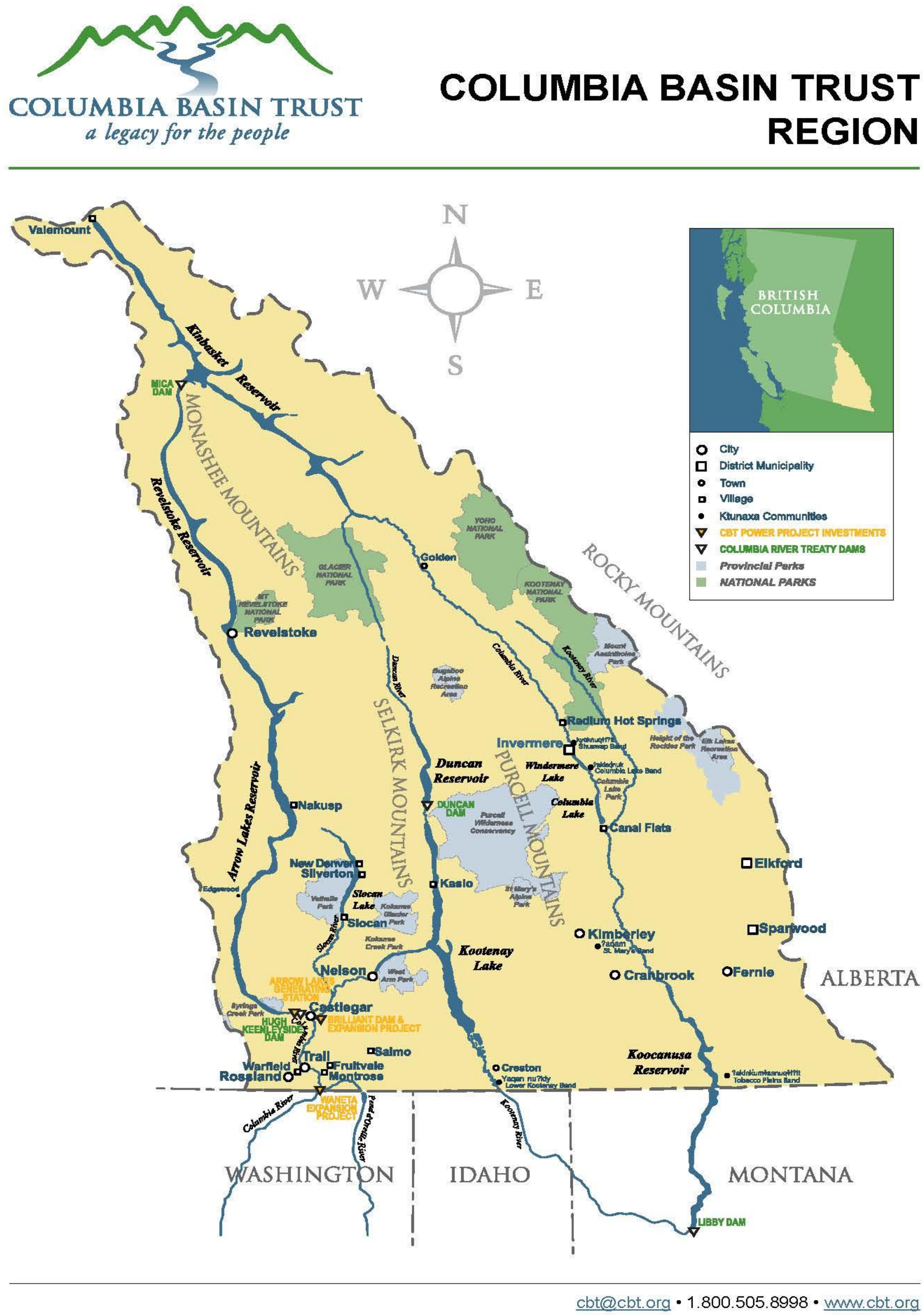

Figure 1 The Columbia Basin Trust Region

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Section 1 Water Quantity Data Inventory

Introduction

This document presents a comprehensive inventory of available water quantity data for the Columbia Basin Trust Region (CBTR). The delineation of the Basin is the area defined by the Columbia Basin Trust Act (Figure 1.1). The objectives are to determine the extent, availability and use of water quantity related data for the Columbia Basin Trust Region and identify key data gaps.

The scope of this inventory will cover longer-term monitoring programs and data sets primarily from active sites, though inactive sites with multiple decades of data have also been included. Point samples and small-scale assessments are generally not included unless the results have been synthesized and published in a report or journal. It is important to note that many private companies collect data that is considered proprietary information. However, any data collected with a permit must be submitted to the government under the Water Act, and Environmental Assessment Act. Since this data is not readily available, it has also not been considered in this assessment.

The water bodies included within the CBTR are rivers/streams, lakes/reservoirs, wetlands, glaciers, snow, and groundwater. Water quantity data is available in the form of precipitation type and amount, stream weirs, lake and reservoir water levels, snow pillow data, glacier areal coverage, and groundwater data. The inventory is organized by water body type. Within each section, the data source, type, collection method (if relevant), how the data is used if the information is available, and access information is provided. Included in the appendix is a list of agencies and non-profit groups interested in water resources in the Columbia Basin.

This report builds on work that has been previously done for the province and the Columbia Basin Trust. Though not a comprehensive list of previous network monitoring analyses, a number of previous studies were consulted Dan Cassleman's water Quantity data inventory report for the Columbia Basin Trust evaluated various federal and provincial networks and their spatial coverage with a short assessment on information gaps (Cassleman 2003). The inventory is obsolete due to the fluid nature of both data collection and government agencies. Beyond Cassleman's report, several provincial government studies were consulted, including: an unpublished report by (Ronneseth 1992), which included a summary of water and watershed related databases; a review of meteorological networks in BC by the Pacific Meteorology Inc. (1996); the former Ministry of Water Land and Air Protection report from M. Miles and associates on British Columbia's climate related observation networks (Miles 2003); the BC Streamflow Inventory (Coulson 1998); an analysis of streamflow in the Kootenay Region (Obedkof 2002); an analyses of the hydrometric/climate network in the Kootenay region (MoE 1997); and a glacier inventory conducted for the CBT and BC Hydro (Trubilowicz 2010).

1.0 Water Quantity Data Types and Sources

1.1 Climate Data

- Total Precipitation
- Snow Fall
- Snow Water Equivalent
- Rain Fall
- Temperature (Average, Max, Min, Heating/Cooling Degree Days)
- Dew Point
- Relative Humidity
- Wind Speed/Direction
- Visibility
- Atmospheric Pressure
- Humidity
- Wind

Numerous agencies maintain climate stations across the CBTR. A summary of data types collected by each agency is provided below.

1.1.1 Environment Canada- Meteorological Service of Canada:

Environment Canada provides access to detailed current and historical weather information acquired using both human observations and automated sensors. The National Climate Data and Information Archive has a variety of online tools to acquire current and historical climate data, including current and historical data at particular locations, historical radar data, Climate Normals, Climate Projections, and Almanac Data. Climate Normals are averages used to summarize climate over a specific time periods and Almanac Data are averages and extreme temperature and precipitation data at a particular site or station.

There are 31 active climate stations with the Canadian Columbia Basin Region (see supplementary spreadsheet), and greater than 250 inactive sites. At present only monthly or daily data can be accessed here:

http://climate.weather.gc.ca/

1.1.2 Ministry of Transportation and Infrastructure

The Ministry of Transportation (MoT) administers a weather network program that includes three main types of weather stations, road weather stations, remote avalanche stations, and frost probe stations. The MoT stations are primarily used for winter conditions. Because most stations are not maintained in the summer, precipitation data cannot be considered accurate through these months due to evaporative loss, or overflowing of gauges. However, 5 stations in the CBTR are maintained through the full season (see supplementary spreadsheet). Road weather stations are generally roadside while

remote avalanche stations can be roadside, mid-mountain, or mountain top. Annual data, one year at a time, can be downloaded here:

https://pub-apps.th.gov.bc.ca/saw-paws/weatherstation

1.1.3 National Oceanic and Atmospheric Administration- National Climate Data Center, United States

The National Climate Data Center (NCDC) hosts Climate Data Online (CDO), a web-based tool to access free archived historical weather and climate from around the world. Daily, monthly, seasonal, and annual measurements of climate variables are available and easily accessed through their online search tools. Only Environment Canada sites listed with the World Meteorological Organization are available. There are 11 in the Basin, and only 8 with more than 15 years of data.

http://www.ncdc.noaa.gov/cdo-web/

1.1.4 Ministry of Forests, Lands and Natural Resources (FLNRO), Wildfire Management Branch

The Wildfire Management Branch maintains active weather stations in the CBTR; the information derived is used for fire prevention and to assess fire risks. The branch maintains fully automated stations and data are transmitted every hour from April to October, and less frequently in the winter. Station coordinates can be found here:

http://bcwildfire.ca/weather/stations.htm

Temperature and cumulative precipitation data are also available through the FLNRO's *Automated Snow Pillow Data* archive. For more Information, please see section 2.2.

FLNRO also operates an experimental watershed where more extensive data collection activities take place, with at least one site in the CBTR. This data is not public.

1. Penticton creek – near Penticton, BC
2. Redfish creek – near Nelson, BC *in the CBTR
3. Sicamous creek – near Sicamous, BC
4. Carnation creek – west of Port Alberni, BC

1.1.5 Canadian Avalanche Association InfoEx Network

The Canadian Avalanche Association Network is a network of professionals that maintain climate stations and make snow observations at high elevations throughout the CBTR. Data are primarily used for recreational travel through alpine terrain. This data is not yet available, though the Cryosphere Research Network is working on making this resource available.

1.1.6 Pacific Climate Impacts Consortium (PCIC)

Climate data from provincial ministries, Environment Canada, BC Hydro, and Rio Tinto Alcan are available through the PCIC web portal, which can be found here: http://tools.pacificclimate.org/dataportal/pcds_map/

1.2 Cryosphere - Snow and Climate

- Snow Depth
- Snow Water Equivalent
- Cumulative Precipitation
- Air Temperature
- Permafrost

1.2.1 Ministry of Environment, British Columbia, Canada

The Ministry of Environment, along with BC Hydro, Rio Tinto Alcan, and the Greater Vancouver Water District, monitor 51 Automated Snow Pillow (ASP) sites around the province of British Columbia. At present, there are 9 sites within the Canadian Columbia Basin Province (see supplementary spreadsheet). Data are collected at hourly time intervals and transmitted via satellite to the River Forecast Centre's receiving station in Victoria. Data include temperature, cumulative precipitation, and snow water equivalent. Data can be downloaded here:

http://bcrfc.env.gov.bc.ca/data/asp/

Manual snow survey data is also collected from around the Province (see supplementary spreadsheet). Measurements are made on the first of each month from January – June, and again on June 15th, eight times per year, though not all stations are sampled one each date. Data include snow depth and snow water equivalent. Current and archived data can be downloaded from here:

http://bcrfc.env.gov.bc.ca/data/survey/

1.2.2 Canadian Cryospheric Information Network (CCIN)

The CCIN provides information and maps on current snow depth and ice across Canada. Summaries on recent changes in snow depth and snow-water equivalent are also available in map and graphic form. The data for snow and ice cover is compiled from satellite imagery provided by NOAA. A number of programs exist that use volunteers to collect snow depth and precipitation totals to create a more complete picture. This data is being used to help model the future changes in snow cover that may occur due to climate change.

http://www.ccin.ca/home/

1.2.3 Canadian Avalanche Association InfoEx Network

The Canadian Avalanche Association Network is a network of professionals that maintain climate stations and make snow observations at high elevations throughout the CBTR. This data is not yet available, though the Cryosphere Research Network is working on making this resource available.

1.2.4 Ski Resort Data

Red, Whitewater, and Revelstoke Mountains have monthly and cumulative snow data available online for the last 6-9 years.

Red Mountain:

http://www.redresort.com/mountain/report/historical-snowfall/

Whitewater Ski Area (1950 masl):
http://www.skiwhitewater.com/whitewater_ski_resort_snow_accumulator.php

Revelstoke Mountain (1960 masl):

http://www.revelstokemountainresort.com/conditions/historical-snowfall

1.3 Cryosphere – Glacier and Permafrost Data

- Mass Balance, geodetic, surface
- Areal Coverage

Mass Balance measurements for glaciers monitored in CBTR (Short-Term):

1. Wapta (Parks Canada)
2. Illecillewaet (Parks Canada)
3. Bryce in the Columbia Icefields (Demuth,GSC)
4. Zlmer (Menounos, UNBC)
5. Kokanee (Menounos, UNBC)

Long-term information on glaciers in the Columbia region is sparse and somewhat limited to primary research publications, human observation and anecdotal information. The latter can be used to create informative collaborations between backcountry professionals (e.g. the Canadian Avalanche Association (CAA)) and scientists. There are a number of agencies and networks presently working to make cryospheric information accessible on the internet.

1.3.1 Canadian Cryospheric Information Network

The CCIN provides general information on current changes and trends in glacier mass balances around the Country and Province. However, none of the long term records on Canadian glaciers are located within the Canadian Columbia Basin.

1.3.2 National Snow and Ice Data Center – World Glacier Monitoring Service

The National Snow and Ice Data Center provides an online tool for acquiring survey data from more than 200 glaciers in British Columbia, including 10 glaciers within the Canadian Columbia Basin.

1.3.3 Global Land Ice Measurement from Space (GLIMS)

The *GLIMS* is an international collaborative project to monitor the world's 160 000 glaciers using optical satellite measurements. Data available include glacier area, geometry, surface velocity, and snow line elevation. The database is made public though an interactive map viewer or through text query. Data is available in a variety of GIS formats, including Google Earth KML files.

http://www.glims.org/

1.3.4 Ministry of Forest, Lands, and Natural Resource Operations

A project is underway with various FLNRO staff to evaluate permafrost regions in northern BC, and this may extend into the mountain regions of the southwest. A map of permafrost extent is available here:

http://www.env.gov.bc.ca/esd/distdata/ecosystems/Permafrost/PermaFrostModel/

1.4 Stream and River Data

- Stream flow
- Water level
- Drainage Area
- Altitude (of gauge)
- Record length and Period of Record (Years)
- Channel width
- Obstruction
- Stream Gradients
- Physical measurements (Temperature, Conductivity)
- Stream Classification

1.4.1 Environment Canada - Water Survey of Canada

The Water Survey of Canada (WSC) is responsible for the collection and dissemination of water resource information across Canada. Across the country, data are contributed from Federal, Provincial, American, and private sources. In the CBTR, data sources include Environment Canada, the Ministry of Environment, BC Hydro, Fortis, and the U.S. Geological Survey. There are 52 active sites in the CBTR.

Historical data including flow, water level, and sediment concentrations for both active and discontinued sites can be downloaded from the Water Survey Website. Users can search by region, site name, or by Federal identification number.

http://www.wateroffice.ec.gc.ca/

The Water Survey uses automated monitoring equipment; at each station water level data is recorded continuously using a data logger. The site is monitored by a technician several times a year to take measurement of water depth and velocity to determine rate of flow or discharge. The measurements are used to calibrate the level data, and the flow data is then estimated from the recorded water level data.

Water Survey Data is also available from the *HYDAT database*. The HYDEX is an associated database that contains inventory information for all inactive and active sites. HYDEX is not available online. Environment Canada also provides a user interface to navigate the data "The Environment Canada Data Explorer", which can be downloaded along with HYDAT here:

ftp://arccf10.tor.ec.gc.ca/wsc/software/HYDAT/

The WSC website also offers a Google map search tool to find sites, and is presently available here:

http://www.wateroffice.ec.gc.ca/google_map/google_map_e.html

1.4.2 Ministry of Environment – Fisheries Inventory Survey Data

Stream data is available through the *Fisheries Inventory Data Query* (FIDQ) web site. The database allows the user to search for a variety of physical and biological data on an individual stream, or streams within a watershed. Databases are available here:

http://a100.gov.bc.ca/pub/fidq/main.do

The Stream Query tool allows the user to obtain the Resource Analysis Branch (RAB) Code, the Watershed Code for British Columbia, the Waterbody Identifier, and stream length of any particular Stream. The Watershed Code provides hierarchical information along a mainstem from the ocean to the watershed. The Waterbody Identifier is used to identify lakes and wetlands within BC, but can also include streams within a watershed.

Under Stream Surveys, the user can find information on physical characteristics, location, channel width, water level, and gradient, and under the stream classification query, the user can find information on stream order, width, gradient, water temperature and conductivity.

2.4 Lake and Reservoir Data

- Lake or Reservoir level
- Perimeter

- Area
- Depth
- Volume
- Elevation

1.4.1 Environment Canada - Water Survey of Canada

In addition to stream and river hydrometrics, the Water Survey of Canada, provides its partners, provides information on reservoir water levels. Data access and availability is through the same website listed in section 2.3.1, and available here:

http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm

1.4.2 Ministry of Environment – Fisheries Inventory Survey Data

The *Fisheries Inventory Database* provides biological and physical information on particular lakes and reservoirs. The Lake Survey Physical Information query allows the user to obtain information on a lake surface area, littoral area, perimeter, volume, mean and maximum depth, and the number of inlets. The Bathymetric maps query allows the user to download .TIF images of bathymetric surveys.

http://a100.gov.bc.ca/pub/fidq/lakes.do

1.6 Groundwater Data

- Groundwater Levels
- Daily Average
- Daily Maximum
- Daily Minimum
- Water Chemistry

1.6.1 Ministry of Environment – Water Protection and Sustainability Branch

British Columbia's *Groundwater Observation Well Network* provides information on groundwater monitoring wells across British Columbia. There are 5 observation wells within the Columbia Basin and a detailed well record is easily obtainable through an online map access tool. Historical groundwater levels, daily averages, maximum, and minimum can be downloaded and historical graphs can be produced. The interactive map is available here:

http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html

The Aquifer Classification database provides an online GIS service. With ArcInfo capability an FTP link to digitized aquifer polygons is available here:

http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/

1.6.2 Ministry of Environment – Water Stewardship Division

There are two main online resources to obtain groundwater well information in BC, the *WELLS database,* and the *BC Water Resources Atlas (BWRA). WELLS* is the provincial groundwater well database. Users can search for water well information from here:

http://www.env.gov.bc.ca/wsd/data_searches/wells/

The *BWRA* is an iMapBC application and allows users to visualize spatial data on a variety of water resource information including water wells, aquifers, surface water, and watersheds. The application allows you to create maps and display spatial information on the above (and other) features. Some queries link to meta-data or actual data. The Water Resources Atlas can be accessed here:

http://www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html

1.6.3 Wildsight Citizen Science Groundwater Monitoring Program

Due to the lack of Provincial and Federal groundwater monitoring, in 2013 Wildsight established Citizen-Science ground water monitoring program. There are currently 3 wells being monitored for groundwater levels as well as chemistry. Data are not presently available online.

1.7 Mapping Tools and Other Resources

1.7.1 iMapBC

iMapBC is a GIS based online application that allows users to visualize and interact with a variety of water resource data. The location of climate stations, hydrometric, and snow survey locations can be plotted, as well as the location of lakes, reservoirs, aquifers, and wells.

http://maps.gov.bc.ca/ess/sv/imapbc/

1.7.2 Ministry of Forests Lands and Natural Resource Operations

GeoBC's *Freshwater Atlas* is a standardized data tool for mapping provincial hydrologic features. Freshwater Atlas data can be viewed through iMapBC, and Google maps vie KML files.

1.7.3 Natural Resources Canada (NRC)

The NRC atlas provides Canada wide scale maps on Watershed, Hydrogeological Regions, Glaciers and Icefields, Wetlands, North American Watersheds, Drainage Patterns, Current Water Levels, Monthly Total Precipitation and Global Climate Change Scenarios.

1.7.4 Rural Development Institute: Digital Basin Portal

The Rural Development Institute is supported through a partnership between Selkirk College and the Columbia Basin Trust. They have developed a digital basin portal that allows one to visualize cultural, social, economic and environmental factors within the Columbia Basin and Boundary regions of British Columbia. The Environmental tab includes information on climate and water, including changes in temperature, precipitation, growing season, streamflow, glacier extent, and water use.

http://www.cbrdi.ca/state-of-the-basin/digital-basin-portal/portal

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Section 2 Water Quality Data Inventory

Introduction

This document presents a comprehensive inventory of available water quality data for the Columbia Basin Trust Region (CBTR). The delineation of the Basin is the area defined by the Columbia Basin Trust Act (Figure 1). The objectives of Phase 1 are to determine the extent, availability and use of water related data for the Columbia Basin Trust Region and to identify key data gaps. At present monitoring stations can be viewed at the following website:

http://www-dev.sgrc.selkirk.ca/cryosphere-monitoring/

The scope of this inventory will cover longer-term monitoring programs and data sets primarily from active sites, though inactive sites with multiple decades of data have also been included. Point samples and small-scale assessments are generally not included unless the results have been synthesized and published in a report or journal, otherwise the data is not considered readily available. It is important to note that many private companies collect data that is considered proprietary information. However, any data collected with a permit must be submitted to the government under the Water, and Environmental Assessment Acts. Since this data is not readily available, it has also not been considered in this assessment.

The water bodies included within the CBTR are rivers/streams, lakes/reservoirs, wetlands, glaciers, snow, and groundwater. Water quality data is available for streams and lakes, but not for precipitation. The inventory is organized by agencies that distribute the information. Within each section, the metrics, collection method (if relevant), how the data is used if the information is available, and access information is provided.

2.0 Sources of Water Quality Data

2.1 Environment Canada: Fresh Water Quality Monitoring

- Major Ions
- Metals (total, extractable, dissolved)
- Nutrients (Nitrogen, Phosphorus)
- Carbon
- Physical (Turbidity, Conductivity, Colour)
- Bacteriological (Fecal Coliform, *Escherichia Coli*)
- Alkalinity, pH

The Fresh Water Quality Monitoring and Surveillance Division of Environment Canada is responsible for monitoring and reporting on water quality throughout the country. The Columbia Basin falls within the Pacific Yukon Water region and the network is composed of both federal and provincial sampling sites managed through federal-provincial agreements. The primary purposes are as follows:

1. Assess threats to freshwater quality and aquatic ecosystems in areas of national and international interest.
2. Meet federal commitments related to trans-boundary watersheds.
3. Support the development, implementation, and assessment of federal regulations.

The information allows the land managers to monitor water quality and identify changes and/or threats to aquatic ecosystems, and support the development of water quality guidelines. Core stations were selected to represent the key human pressures on water quality in Canada's more populated drainages. Local stations were also chosen to provide more local information.

Site information and data can be found here:

http://www.ec.gc.ca/eaudouce-freshwater/default.asp?lang=En&n=EFDA57C6-1

In addition, Environment Canada has published current water quality status and trends (Canada 2011)and can be found here:

http://publications.gc.ca/collections/collection_2011/ec/En154-63-2011-eng.pdf

2.2 Ministry of Environment: Environment Protection Division

The MoE website listed below has a comprehensive list of objectives, guidelines, and reports based on long-term monitoring, one-time site monitoring, paleolimnological, studies, attainment objectives, and sediment studies.

http://www.env.gov.bc.ca/wat/wq/wq_sediment.html#kootenay

http://www2.gov.bc.ca/gov/topic.page?id=500E145665274DB980A7B61735E5C55F

2.3 GEMS: Global Environment Monitoring System

GEMS is a United Nations Environmental Program focused on inland water quality issues worldwide. GEMS' two goals are to improve water quality monitoring and assessment and to determine the state and trends of regional and global water quality. The website provides the surface and groundwater quality data and statistics, for over 100 parameters, from all participating countries. The

data is compiled from data submitted by governmental and non-governmental groups. GEMS also has a quality assurance and quality control policy to ensure the reliability and consistency of the data that is submitted. All of the methodologies used in the program are published. The GEMS data in the Columbia basin is provided by Environment Canada.

Choosing a station from the interactive map leads to a query of the parameters that can be chosen, from which the data can be downloaded or summary statistics can be viewed. Since data is supplied from Environment Canada, measured parameters will be the same reported through the Fresh Water Quality Monitoring Program.

http://www.gemstat.org/default.aspx

2.4 CABIN: Canadian Aquatic Biomonitoring Network

- Major Ions
- Physical Parameters
- Metals (total, extractable, dissolved)
- Nutrients (Nitrogen, Phosphorus)
- Benthic Macroinvertebrates

CABIN is an Environment Canada program that aims to promote inter-agency and citizen science collaboration and data sharing to create a more consistent database on freshwater quality and ecosystem conditions. Despite this aim, data is not available to the general public nor to other scientists who have not undergone CABIN training. The program uses the Reference Condition Approach for site assessment; this model allows data collected by trained citizens to be used to asses stream health via statistical ordination. CABIN uses benthic invertebrate communities as the biometric in conjunction with physicochemical information to assess the health of freshwater ecosystems in Canada. All participants in the CABIN program follow the same protocols to ensure data consistency.

https://www.ec.gc.ca/eaudouce-freshwater/default.asp?lang=En&n=50947E1B-1

2.5 IHA: Interior Health Authority

- Bacteriological (Fecal Coliform, *Escherichia Coli*)
- Metals
- Nutrients (Nitrogen, Phosphorus)
- Physical (Turbidity, Conductivity)
- Hardness
- Alkalinity, pH

The Interior Health Authority monitors drinking water quality as well as recreational water quality. The drinking water quality monitoring focuses on parameters that affect human health, including *E. coli*, fecal coliforms and some chemicals. Interior Health takes samples monthly from 1900

water systems. Bacteriological samples are collected weekly to monthly and full chemical analyses are tested every 3-5 years. Larger communities have their own monitoring systems in place, though still checked by IHA, and their data is available by contacting them directly. Interior Health Authority results are found here:

http://www.interiorhealth.ca/YourEnvironment/DrinkingWater/Pages/DWSampleResults.aspx
Inspection reports can be found here:

http://www.interiorhealth.ca/YourEnvironment/InspectionReports/Pages/default.aspx

The recreational water quality data includes *E. coli* and historically fecal coliforms. They are monitored during the swimming season, usually from ~ May 1st to September 1st. The data is updated as new results are received.

http://www.interiorhealth.ca/YourEnvironment/RecreationalWater/Pages/default.aspx

2.6 DFO: Department of Fisheries and Oceans

- Aquatic Invasive Species
- Biotechnology
- Climate Change
- Fish Habitat
- Fisheries Science
- Species at Risk

Fisheries and Oceans Canada has a freshwater research program that is active across Canada. They collaborate with a number of different partners, including other government departments, universities and NGOs. There is a list of all the research projects that is current as of April 2013. The research topics include: aquatic animal health, aquatic invasive species, aquaculture science, biotechnology, climate change, ecosystem assessments, fish habitat, fisheries science, hydrographic products and services and species at risk.

http://www.dfo-mpo.gc.ca/science/Freshwater-Science/index-eng.html

Report can be searched and downloaded from the Waves online library:

http://waves-vagues.dfo-mpo.gc.ca/waves-vagues/

2.7 BC Fisheries

BC Fisheries in conjunction with Fisheries and Ocean Canada maintains a Fisheries Information Summary System (FISS), which provides fish and fish habitat data for water bodies in BC and the Yukon. The data base also includes information on invasive species, and can be found here:

http://www.env.gov.bc.ca/fish/fiss/

2.8 Citizen science groups

- Stream Temperature
- Water Chemistry
- Invertebrate and Habitat Data

2.8.1 Columbia Basin Water Quality Monitoring Project (CBWQMP)

Supported by the Columbia Basin Trust, the CBWQMP is a collaboration between CBT, Environment Canada and 8 citizen science watershed groups that are active in the basin. Each group has been trained in CABIN protocols to ensure quality standards. The groups are:

- Arrow Lakes Stewardship Group
- Friends of the Lardeau River
- Salmo Watershed Streamkeepers Society
- Slocan Streamkeepers Society
- Golden Wildsight
- Invermere Wildsight
- Joseph Creek Streamkeepers
- St Mary Valley Rural Residents Association

http://cbwn.ca/dev/water-quality-monitoring/

2.8.2 Wildsight Citizen Science Groundwater Monitoring Program

Due to the limited availability of Provincial and Federal groundwater monitoring data, in 2013 Wildsight established a Citizen-Science ground water monitoring program. There are currently 3 wells being monitored for groundwater levels as well as chemistry. Data are not presently available online. As with other data gaps, groundwater data is often collected by private companies and proprietary data could fill these gaps.

2.9 Online Resources

2.9.1 Rural Development Institute: Digital Basin Portal

The Rural Development Institute is supported through a partnership between Selkirk College and the Columbia Basin Trust. They have developed a digital basin portal that allows one to visualize cultural, social, economic and environmental factors within the Columbia Basin and Boundary regions of British Columbia. The Environmental tab includes information on climate and water, including changes in temperature, precipitation, growing season, streamflow, glacier extent, and water use.

http://www.cbrdi.ca/state-of-the-basin/digital-basin-portal/portal

2.9.2 Biodiversity Atlas

The Biodiversity Atlas project was initiated through a Fish and Wildlife Compensation Program grant and is maintain by the Selkirk College's Geospatial Research Centre. Funding is provided by the CBT, The Nature Trust of BC, FortisBC, and other stakeholders. The interactive map includes the CBTR region and allows you to download biodiversity studies, including those related to freshwater species and their ecosystems that have been conducted at various sites. Conservation and restoration areas can also be found. The map is available here: http://biodiversityatlas.org/maps/index.html

References Section 2

Canada E (2011) Water Quality Status and Trends of Nutrients in Major Drainage Areas of Canada. Environment Canada,

Part 3 Data Analyses

Water in the Columbia

The availability and quality of water is arguably one of the most important issues facing our ever-expanding human population. Beyond our own needs, sustainable water resources are essential to the proper functioning of nearly every ecosystem on the planet. The Columbia River Basin incorporates areas from six US states and one Canadian province (Figure 1.0). The Canadian portion of the Columbia Basin comprises only 15% of the total area; however, since it includes most of the high elevation area, this region provides 30-40% of the total annual runoff (Hamlet and Lettenmaier 1999b; Cohen et al. 2000). The Columbia Basin supports over 400 dams producing a large portion of the energy needs of the Pacific Northwest, several unique ecosystems, numerous fish species, agriculture, and a growing population. The timing of volume and discharge, and their sensitivity to climate change, is therefore of widespread significance for both ecologic and economic reasons.

Water Quantity

The headwaters in the Columbia are primarily fed by snowmelt, and thus winter conditions are an important variable in controlling both the volume and timing of flow. This nival characteristic creates a redistribution of water so that winter precipitation is temporarily stored and contributes to spring and summer runoff. Glacier contributions can be significant in some streams in the late summer when annual snow resources have been depleted. Groundwater contributions are relatively small and comprise late summer to winter baseflow conditions. Because of the basin dependence on snowmelt, the discharge in the Columbia Basin is particularly sensitive to shifts in dominant Climate Modes as well as global climate warming.

Climate Modes, or Climate Indices refer to statistical relationships between oceanic conditions and weather patterns. Air masses that carry moisture to western North America and the Columbia Basin generally originate in the Pacific Ocean where their properties are highly modified by sea surface temperatures, and their trajectories controlled by atmospheric conditions (e.g. the location of the jet stream). Previous work has shown that the a number of Climate Indices are important drivers of the western North American climate. These indices include: the Pacific Decadal Oscillation (PDO), the El Niño Southern Oscillation (ENSO), the Artic Oscillation (AO), and the Pacific/North American Pattern (PNA). These indices strongly control temperature and moisture delivery to western North American, and thus strongly control climate factors that influence water availability including precipitation, temperature, and glacier mass balances (Moore et al. 2009; Gobena et al. 2013; Whitfield et al. 2010; Hamlet and Lettenmaier 1999a; Stahl et al. 2006; Abatzoglou 2011). Because Climate Modes are affected by greenhouse gas-induced climate warming they are not strictly independent. Greenhouse gas-induced climate warming refers to the increase in global average atmosphere and ocean

temperatures that have occurred since 1880, with a large fraction likely due to the increase in greenhouse gas emissions from anthropogenic activities, such as fossil fuel combustion (IPCC 2013).

Warmer temperatures mean less precipitation falls as snow, summer evapotranspiration increases, and glacier contributions decrease. These changes can translate into earlier peak flows and reduced summer flows (Cohen et al. 2000; Barnett et al. 2005; Hamlet and Lettenmaier 1999b; Schnorbus et al. 2012; Stahl and Moore 2006; Bolch et al. 2010). In the Columbia Basin of Canada, temperatures in the last century have risen by 1.2°C (Jost 2013). A shift toward an earlier freshet and center volume of flow (the date at which half the annual volume has been discharged) has been observed in streams across western North America (Stewart et al. 2005; Regonda et al. 2005)

In addition to the main climatic variables, there are a variety of hydrological controls that affect water resources across the diverse landscape of the Columbia Basin. These include direct human impacts such as the construction of dams and channel modifications, deforestation, urbanization, surface water and groundwater extraction, wildfires, and insect related tree-mortality. All of the above factors have the potential to modify water flow paths and affect the availability and seasonality of water flow. The proposed new Water Sustainability Act in BC aims to make improvements in areas that will be impacted by climate change (MoE 2014). The proposed legislation will require the consideration of water quantity in land-use decisions, and will require environmental flow regulation to protect stream health and aquatic environments. The legislation further included the regulation and protection of groundwater and the measurement and reporting of water use. The recommendations provided here support the desired outcomes from the new act.

Water Quality

A variety of both natural and anthropogenic factors can lead to declines in water quality including the effects of storms, erosion, landslides, geology, atmospheric contaminants, and land-use. Climate change has the potential to exacerbate all of the above and introduce new and unexpected problems. The Columbia River Basin incorporates areas from six US states and one Canadian province (Figure 1.0) and supports over 400 dams producing a large portion of the energy needs of the Pacific Northwest, several unique ecosystems, numerous fish species, agriculture, and a growing population. Water quality is of widespread significance for both ecosystem health and human and wildlife consumption and use.

Natural controls on water quality include the effects of surficial geology, landscape features, and climate. Some areas may contain naturally high concentrations of trace metals (e.g. As, Se, Pb), or ions (e.g. fluoride) that are harmful to health, or other compounds that cause problems through staining or precipitation (hardness, iron concentrations. Geology can also influence the acidity/alkalinity of waters as can terrestrial and aquatic vegetation. The latter will further influence organic carbon and nutrient concentrations. Vegetation type and percent coverage will also influence how contaminants deposited in the terrestrial environment are processed and ultimately delivered to flowing water or lakes. Climate controls include storms or permafrost degradation that lead to erosion or landslides that suspend

material in water and/or block channels, as well as drought. These can lead to the concentration of dissolved species in water.

Anthropogenic contaminants that threaten aquatic, terrestrial, and human life can enter surface and groundwaters through runoff from urban areas, industrial effluent, and runoff from agricultural, pastoral, and cleared forest areas as well as from the atmosphere. Nutrients introduced through human waste or agricultural practices can lead to eutrophication, loss of diversity, a shift in species composition (often to undesirable species), murky waters, choked channels, O_2 reduction and fish kills, and can be unsafe for human consumption (NO_2^-). Recreational activities can lead to the transport and establishment of exotic species that can outcompete native species, overgrow, and threaten biodiversity, habitat, and human water resources. Finally, the atmosphere can transport nutrients and contaminants from outside the geographical or political boundaries. In many cases it will be hard to recover from many types of pollution and in some cases contamination of groundwater can be permanent.

At present we are undergoing an unprecedented change in the global climate and moving towards a period of no analogue in the hydro-climate system. These changes have strong implications for societal water use, and will profoundly impact water quality and ecosystem structure and function. These changes will stress biodiversity, ecological flow requirements, and reduce habitat connectivity. The proposed Water Sustainability Act will require the consideration of water quality and quantity in land-use decisions, and will require environmental flow regulation to protect stream health and aquatic environments. The legislation further included the regulation and protection of groundwater and prohibits the harmful dumping of human and animal waste, pesticides and fertilizers. The recommendations provided here support the desired outcomes from the new act.

Analyses Overview

This analyses presented here are intended to provide and a first order assessment on water quantity and quality data and knowledge gaps in the CBT region. The analyses examine factors that influence water supply including regional climate patterns, global climate change, and anthropogenic influences. These factors are then related to specific water resources, including glaciers, rivers, groundwater, and lakes. With respect to water quality, the document examines the major stressors and evaluates how well various organizations are tracking potential water quality issues. Through the discussion, gaps in available data and knowledge are highlighted and recommendations are made. Throughout the document references to the regions within the CBT are made; these refer to statistical divisions and are illustrated in Figure 3.0.

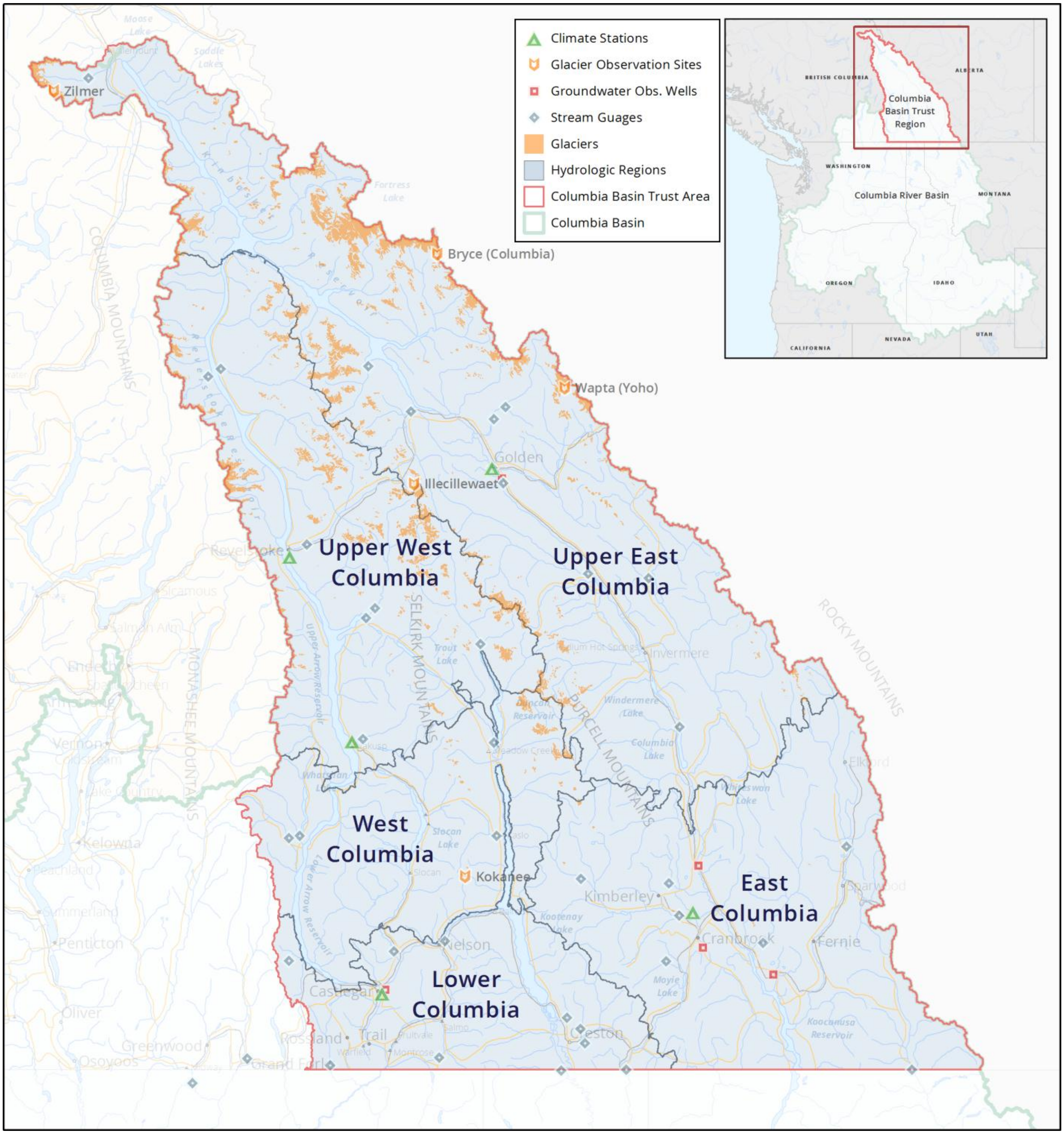


Figure 3.0 The Columbia Basin Trust Region (CBTR) in southeastern British Columbia. The CBTR is divided into five statistical hydrologic regions based on analysis conducted in Section 5.

3.1 Climate Change and the Hydrologic Cycle

The term 'climate change' refers to changes in the average distribution of weather patterns over decadal and longer time scales. Over the time scales of interest here, climate changes in the Columbia Basin Trust Region (CBTR) arise due to both natural climate variability and greenhouse gas-induced climate warming. Natural climate variability in the CBTR refers to the somewhat cyclic changes in ocean-atmosphere circulation patterns that originate in the Pacific Ocean. These patterns in sea-surface temperatures and pressures can be statistically related to dominant weather patterns and the oscillations tracked over time, we refer to these here as Climate Indices, also known as Climate Modes (NOAA 2013a). Because Climate Indices are affected by greenhouse gas-induced climate warming they are not strictly independent. Greenhouse gas-induced climate warming refers to the increase in global average atmosphere and ocean temperatures that have occurred since 1880, with a large fraction likely due to the increase in greenhouse gas emissions from anthropogenic activities, such as fossil fuel combustion (IPCC 2013).

Climate change, regardless of the cause, influences precipitation type and amount as well as temperature variables. These factors have a strong influence on the hydrologic cycle and therefore a strong influence on water availability within the CBTR. Climate and weather patterns affect the amount and type of water that arrives to the basin, evapotranspiration rates, the amount of water stored as snow or ice, groundwater-surface water interactions, and catchment properties that influence runoff and the degree of infiltration.

3.1.1 Climate Indices

Air masses that carry moisture to western North America and the Columbia Basin generally originate in the Pacific Ocean where their properties are highly modified by sea surface temperatures, and their trajectories controlled by atmospheric conditions, (e.g. the location of the jet stream). Changes in regional ocean-atmosphere relationships can be described by Climate Indices, where sea-surface temperature and pressure changes are statistically and mechanistically related to a subset of climate patterns. Previous work has shown that the following Climate Indices, Pacific Decadal Oscillation (PDO), the El Niño Southern Oscillation (ENSO), the Artic Oscillation (AO), and the Pacific/North American Pattern (PNA) strongly control temperature and moisture delivery to western North American, and thus strongly control climate factors that influence water availability including, precipitation, temperature, and glacier mass balances (Moore et al. 2009; Gobena et al. 2013; Whitfield et al. 2010; Hamlet and Lettenmaier 1999a; Stahl et al. 2006; Abatzoglou 2011). In the analyses reported here, we find the Northern Oscillation Index (NOI) significantly describes a large fraction of variability for both climate and hydrometric variables (Section 4).

The PDO is a direct effect of conditions manifesting from ENSO, but unlike ENSO its manifestation occurs over decadal time scales. The effects of positive (warm) and negative (cool) phase PDO and ENSO are similar in the Pacific Northwest. The PDO index is based on oscillations in sea surface temperatures in the North Pacific and specific phases last 20-30 years (Figure X). During Cool Phase PDO, winds are

blowing from the North and upwelling occurs along coastal ocean currents. This phase is related to cooler and wetter winters in the Pacific Northwest (Trenberth and Hurrell 1994). In contrast, during the warm phase winter winds along the coast of the North Pacific blow from the south. The Warm phase of the PDO is associated with warmer temperatures, with milder and drier winters in the Pacific Northwest.

The El Niño Southern Oscillation is based on oscillations in equatorial sea-surface temperatures that shift phases every 1-7 years (Ropelewski and Halpert 1986) (Figure X). Because ENSO effects the location of the jet stream, weather conditions in the Pacific Northwest are affected. During warm (El Niño/positive) phases, the jet stream is diverted south, leaving the Pacific Northwest warmer and drier. During cool (La Niña/negative) phase, the jet stream flows directly toward the Pacific Northwest bringing cooler wetter winters. During warm (El Niño) phases, the Pacific Jet strengthens and is diverted south while the polar jet weakens and is diverted north. During cool (La Niña) phases, the Pacific Jet weakens and the Polar Jet becomes strong yet variable in position.

The Pacific/North American Pattern is also associated with strong fluctuations in the strength and location of the jet stream. When the PNA is in a positive phase, the jet stream is shifted eastward and high pressures exist over western North America, which results in above average temperatures in western Canada for fall, winter, and spring months. During the negative phase, the jet stream is shifted towards the west bringing cooler air into western Canada and above average precipitation (NOAA 2013b). There is a strong connection between ENSO and the PNA, with positive PNA phases associated with El Niño phases, and negative PNA phases associated with La Niña phases.

The Northern Oscillation Index is based on differences in sea-level pressure anomalies between Darwin Australia and the North Pacific high. The index is strongly linked to atmospheric circulation patterns in the extra tropics, influencing climate patterns at various time scales in the North Pacific and therefore, also, western Canada (Schwing et al. 2002). The NOI is similar to the Southern Oscillation Index as a northern counterpart, but is larger in amplitude and highlights events not captured by the SOI

Uncertainties

- Long term evolution of Climate Indices and their relationships to temperature and precipitation patterns in the Columbia Basin.
  - Instrumental records of Pacific sea-surface anomalies, and temperature and precipitation in the CBTR only extend at most ~100 years. These records may not be representative of longer term variability and future climate states.

- Future manifestations of Climate Indices and their relationships to hydrologic processes in the Columbia Basin.
  - At present, it is unclear to what extent anthropogenic climate change will influence the expression of climate indices in the Columbia Basin; it is likely that warming will change the

intensity, frequency of modal direction (negative/positive), and perhaps the oceanic loci of these ocean-atmosphere relationships.

- It is unclear if we can expect decadal variability in the PDO to look like it did in the 20th century.

Recommendations

- Support investigations how these climate modes change in the CMIP5 models.
- Support efforts to determine if the effects of the NOI, PDO, the PNA, and ENSO can be disentangled – is there independent information contained in each index?
- Support the ongoing monitoring of the state of ENSO/PDO/PNA/NOI and their relationship to climate in the CBTR.

3.1.2 Greenhouse Gas-induced Warming and Climate and Hydrologic Model Projections

Since 1880, the global average land and ocean surface temperatures have increased by 0.85 (± 0.2)^{0}C, with much of this increase occurring since 1980 (IPCC 2013). Over the next century global average temperatures are projected to increase by (1.1 to 4.8 ^{0}C) with the rate and magnitude contingent on various greenhouse gas emissions scenarios (IPCC 2013). Because increases in temperatures strongly influence evaporation rates and the movement of air masses, climate warming is expected to intensify the global hydrologic cycle.

To evaluate local scale impacts of climate change, various methods have been developed to downscale projections from Global Circulation Models. Downscaled climate model projections can be used in conjunction with hydrologic models to predict changes in the volume and timing of flow in a given river system. Hydrologic models themselves vary in scale from a local small stream catchment to regional projections for large rivers, such as the Columbia River. These models are important and useful tools for predicting future changes, allowing for adaptive water management strategies.

Despite the clear usefulness of streamflow projections, there are considerable uncertainties associated with these models. Difficulties arise because the downscaled climate change scenarios that drive the hydrologic models are challenging to construct for the mountainous geography of the region. Steep topographic variation causes corresponding variation in temperature and precipitation, and calibration and validation data are often unavailable at a high enough resolution or at high elevations. As a result, there are often significant differences between climate model runs in the sign and magnitude of critical input variables such as seasonal precipitation. Furthermore, due to variation in calibration choices, baseline parameter values, etc., there can be significant differences between hydrologic model runs as well (e.g. Hamlet et al. 2013b). The latter is particularly significant in the CBTR where different model treatment of glaciers can lead to large changes in model output. In addition, changes in human

land-use can significantly alter the response of any river system to projected climate changes (see below). The most pressing issue for BC hydrologic regimes is the strong control of Pacific Climate indices on climate and water resources. Calibration data for models should be longer than the cycles of these variables, though they typically are only a few decades long. Since phases of the PDO can last up to 35 years, records used in the models should be greater than 70 years (Miles 2003). In reality, however, any length of time may be insufficient due to the non-stationarity of climate change. These uncertainties represent significant knowledge gaps for future water resources in the CBTR.

Several studies have focused on the hydrologic impacts of climate change in mountain regions e.g.(Viviroli et al. 2011; Barnett et al. 2005). In general, snow-melt dominated mountain regions are expected to undergo significant shifts in the timing of flow, with a trend towards an earlier spring peaks and reduced late summer flows. Increased peak flows may mean increased flood risks (Cohen et al. 2000), and the impacts of low flows on both economic and ecological factors are numerous. To some degree reservoirs can mitigate the need for water resources downstream.

Several studies have examined the impacts of climate warming on hydrometrics in the Columbia Basin specifically (Hamlet and Lettenmaier 1999b; Schnorbus et al. 2012; Cohen et al. 2000; Hamlet et al. 2013a). Though there is variation in the downscaled global climate model predictions for British Columbia as well as in hydrologic model output, several important features are consistent.

- Warming will continue into the 21st century with expected increases in global temperature by 1.1-4.8 ^{0}C by 2080 (IPCC 2013).
- In the CBTR mean annual temperatures are expected to increase by 1.9 ^{0}C (+1.2 to 2.8 by 2050^{0}C)(PCIC 2013).
- In the CBTR, mean annual precipitation is expected to increase by 5% (-3 to 10%) by 2050 (PCIC 2013).
- In the CBTR winter precipitation is expected to increase by +8% (-2 to+17%) by 2050; however, snowfall is expected to decrease by -5% (-12 to +6%) in the winter, and by -48% (-68 to -9%) in the spring (PCIC 2013).
- Precipitation in the summer is expected to decrease by -6% (-18 to 0%) by 2050 (PCIC 2013).
- Annual flows are expected to increase in the Mica basin by +5 to +22% by 2050, and in the Columbia at Birchbank by +5 to +15% by 2050 (Hamlet et al. 2013b).

Despite projected increases in annual flow, regional water shortages in the late summer and early fall can still be expected to occur. Warmer temperatures mean less precipitation falls as snow and less water is stored in the catchment for runoff in the summer. In addition, an earlier freshet moves the volume of annual discharge earlier in the year, and increased temperatures will increase evapotranspiration rates. All these changes combined will lead to decrease in late summer flow, a time when water resources are already limited. Predicting summer low flows is particularly important from a water resource standpoint. Low flows in the summer coincide with high human demands for irrigation and domestic use, both of which may increase in a warmer climate. A higher need for electricity

translates to increased water release to generate the electricity, and less water stored. Low flows can have negative consequences for aquatic organisms by reducing available habitat and increasing the temperature of water. Because land-use effects are often not explicitly considered in the same hydrologic models used to infer climate- related impacts on hydrology, it is important to consider how these effects may amplify or compound future climate and water yield predictions discussed above.

In sections (2-5), the impacts of natural climate variability and greenhouse gas induced climate warming on the various water resources types are discussed and in some cases analyzed. The analyses in the sections below evaluate historical relationships between water resource types and climate variability both through the instrumental record and through literature reviews of paleo-records.

Uncertainties

- Long term evolution of Climate Indices and their relationships to temperature and precipitation patterns in the Columbia Basin.
    - There are insufficient climate stations with long term data to be able to generalize conditions in a sub-regional context.

3.2 Catchment Disturbances

The Canadian portion of the Columbia basin spans a variety of landscape types from lower elevation regions in the south that are drier and more heavily populated to the northern alpine catchments that are steep and contain perennial snow and ice. Aside from climate changes, water resources are heavily influenced by land-use change including wildfires, forest harvesting, insect infestations, construction of logging roads, and rural land use activities. A brief discussion on the hydrologic effects of catchment disturbance is outlined here. Because land-use effects are often not explicitly considered in the same hydrologic models used to infer climate related impacts on hydrology, it is important to consider how these effects may amplify or compound future climate and water yield predictions discussed above.

In general the effects of forest removal through harvesting, insect outbreaks, or wildfires, cause an increase in water yield. A reduction in tree canopy cover, through harvesting, insect outbreaks, or wild fires, causes a reduction in interception, an increase in drop size and velocity, and reduces evapotranspiration. In addition, surface runoff is often increased and infiltration rates decreased when the forest floor and root mass is removed (Binkley 2012). A healthy forest floor and root mass act to stabilize soil aggregates thereby increasing pore space and the ability of the soil to hold water and increase infiltration. Compaction, which can occur with harvesting (Moore and Wondzell 2005) and an increase in soil hydrophobicity, which can occur with forest fires (DeBano 2000), will further increase runoff and reduce infiltration. A reduction in crown cover and forest removal can also increase snow accumulation. In British Columbia, clearcutting may increase snow accumulation by 5-70% as compared to undisturbed forest areas; the effect can be somewhat offset by increases in evaporative loss and sublimation in these exposed areas (Winkler et al. 2010). In addition, logging roads can increase surface flow and contribute to sediment yield.

In the CBTR, most impacts are observed in the snowmelt season during peak runoff, and the effects are often greater at higher elevations (BC Ministry of Forests 1995). Increases in yield are related to decreases in evapotranspiration, and infiltration, and to increases in snow accumulation. A study from a high-elevation, snow dominated catchment in northern Idaho found that catchments with logged areas between 21-33% showed an increase in annual yield by 51-80% (King 1989). A summary of paired catchment studies indicate that peak flows have been observed to increase by 13 to 42% (Moore and Wondzell 2005). Similar effects have been observed with forest fires, The Eden fire in Salmon Arm (1973) burned ~50% of the watershed and increased yield during peak flow season by 24% (BC Ministry of Forests 1995).

Mountain pine beetle effects differ because the mortality and changes in tree canopy take place over a number of years. A study in headwater catchments of Colorado found that stands in the ‘Red Phase’ of death, when needles are retained, showed that snow accumulation was similar to healthy stands, but snow melt was faster, causing melt to occur up to one week earlier. During the ‘Grey Phase’, after the loss of the needles, snow accumulation was 15% higher, and snow melted faster due to an increase in radiative light penetration (Pugh 2011).

The effect of a loss of forest cover causes an increase in peak and storm flow, and increased risk of flooding (Conedera et al. 2003; British Columbia Forest Practices Board 2007). The effects and risk due to a loss of forest cover are diminished as the forest regrows; though, the recovery time can take 10-20 years, or even longer in snow dominated catchments (Moore and Wondzell 2005). Finally, climate change has the potential to influence the frequency of both forest fires and insect infestations, as does human occupation. With increased temperatures, fires in southeastern British Columbia are expected to increase in frequency and intensity (Haughian 2012).

Knowledge Gaps

- There is uncertainty in the future risk of insect infestations due to climate change.
- Changes in fire frequency associated with climate change.
- Changes in human-caused fires owing to increased or altered occupancy of forest lands.

Recommendations

- Support and encourage research in forest hydrology with respect to forest health.
- Support research in the incorporation of land-use into model projections, i.e., model streamflow in the CBTR including the effects of natural climate variability (Pacific climate indices), anthropogenic climate change, and catchment related impacts, including logging, and changes in insect kills, fire frequency, and human needs with climate change.

3.3 Historical Climate Changes in the Columbia Basin of Canada

Data Availability and Coverage

Though at least three government agencies maintain approximately 100 annual climate stations across the basin, access to long-term data sets is severely limited. By far the most comprehensive climate data network is maintained through the Ministry of Forests Lands and Natural Resource Operations (FLNRO) Wildfire management branch with approximately 49 stations in the CBTR. The data is not available online and is difficult to access without knowing the appropriate contact. Environment Canada at present has 31 active stations in the CBTR, 11 of which are reported through the World Meteorological Organization. Long-term data sets are only available to download through the National Climate Data Center online resource, and only 8 of these stations have greater than 15 years of data. At present, Environment Canada does not have online access to multiple monthly or annual average data; only one month of daily data can be downloaded at a time. The Ministry of Transportation has ~40 stations, though only 5 are maintained year round. MoT data can only be downloaded for one year at a time. In summary, only 8 long-term data sets are available (hosted through a foreign country), from >60 stations with more than 30 years of data. This discrepancy highlights resource issues within the local and federal government with respect to both personnel and data warehousing. Various US government and non-government agencies have easily accessible data; their structure and web-based interfaces can serve as a model for Canadian government agency databases. Please see Phase 1, Part 1: Data Inventory and associated .xls files for details on the climate network in the CBTR.

In addition to accessibility, the data itself is biased towards the Lower Columbia Region (Tables 3.1.1 and 3.1.2), and elevations below 1000 masl). Because of the spatial scale of the CBTR and the range in landscape diversity and climatic regions, the present network of climate stations is inadequate in representing both higher altitudes and higher latitudes. The most comprehensive method for evaluating spatial changes in climate in complex terrain is through the Parameter Elevation Regression Independent Slopes Model (PRISM). PRISM models can provide information at small spatial scales based on the integration of available data and digital elevation maps. As always with models, the quality of the data output is proportional to the quality of data input. More critically, adequate resolution of data is required to model future climate changes at local scales. This task is performed by 'downscaling' regional climate models and this requires enough spatial and historical observational data to adequately determine the average conditions. Minimum data requirements are typically set around one station per 100- 250 km^2 (Miles 2003; WMO 1986). An additional complicating factor in British Columbia is that climate is strongly controlled by natural variability on cycles that range from annual to decadal time scales. Data used in any climate or hydrologic model should be longer than any one cycle in these variables, though this standard is rarely applied (section 2.2).

Table 3.1.1 Stations by region and altitude. Data sources include BC Hydro, Environment Canada, Ministry of Transportation and the FLNRO snow pillow and wildfire management climate stations

Station Altitude	Upper East	Upper West	East	West	Lower	Total
<1000 masl	6	12	13	3	23	57
1000-2000 masl	11	8	14	3	3	39
>2000 masl	3	1	1	2		7
Total	20	21	28	8	26	103

Table 3.1.2 Station density, the number of stations is normalized to the area of each region. Data sources include, BC Hydro, Environment Canada, Ministry of Transportation and the FLNRO snow pillow and wildfire management climate stations

per 10,000 km^2	Upper East	Upper West	East	West	Lower
<1000 masl	3	6	7	3	27
1000-2000 masl	5	4	8	3	4
>2000 masl	1	1	1	2	0
Total	9	11	16	8	30

Here we evaluate the data coverage using criteria outlines by the World Meteorological Organization (1981, 2008) and the needs of climate modellers (Miles 2003), where one precipitation station is required for a 100-250 km^2 area, with a tolerance up to 1000 km^2 in difficult conditions. Criteria are not provided for temperature, though we employ the same criteria here, and evaporation should be monitored for every 50 000 km^2. We are unable to evaluate the latter since data is at present unavailable from the Environment Canada online database.

Based on the above criteria, the density of climate data range from only 7 to 30% of the ideal spatial coverage by region, or 19-76% of the minimum requirements as recommended by WMO (WMO 1981, 2008)(Table 3.1.3). With respect to temporal coverage, only 10 stations, biased to the Lower and East Columbia regions have greater than 50 years of data (Table 3.1.4), and only 6 stations with greater than 70 years of data.

Table 3.1.3 Percent station coverage for each region based on the WMO guidelines. Recommended minimum coverage for Mountain regions is one station per 250 km^2, with an ideal density at 100 km^2.

	Upper East	Upper West	East	West	Lower
% of Ideal	7%	14%	16%	8%	30%
% of Minimum	19%	34%	39%	19%	76%

Table 3.1.4 Stations by region and record length. **Data sources include, BC Hydro, Environment Canada, Ministry of Transportation and the FLNRO snow pillow stations. Start data for FLNRO wildfire management stations are not available online.**

Length of Record (Years)	Upper East	Upper West	East	West	Lower	Total
<15	4	8	7	1	2	22
>15	13	8	19	5	22	67
>30	3	4	11	2	12	32
>50	1		3	2	4	10
>75			2	1	3	6

The discussion above is based primarily on the ability of climate and hydrologic modellers to adequately represent a region for future projection of water availability; however, the ability for land-managers to assess public safety factors related to the climate events should also be considered. Anticipated climate changes included increase in the severity and frequency of extreme events. Of particular relevance to the Columbia region are the effects of floods and drought. In the CBTR, flood events often occur from heavy rain, or rain on snow events, even in low snowfall years. As such, it has been suggested that capacity to measure short-term rainfall intensity (10 minute precipitation) should be initiated as well as a radar system within the region would help predict the onset of such storms.

Additional gaps with respect to climate monitoring are the condition of ice on rivers, lakes, and reservoirs. The timing and thickness of ice formation and loss is an important indicator of climate related changes that can influence a variety of water resource concerns. Ice jams can lead to the damming of rivers and flooding, and changes in the timing of ice on and ice off influence phenology, evaporation, and water temperatures. Since most of the metrics are subjective evaluation (not through instrumentation), citizen science groups can be trained to observe ice related metrics.

3.3.1 Data Analyses

Introduction

The Columbia Basin in Canada (Figure 3.2.1) spans a wide range of climate zones from the relatively warm and dry valleys in the southwestern region to cold wet alpine regions in the northeast. The diversity in landscape types also means that climate and weather can be distinctly different over relatively short distances, from, for example, rapid changes in altitude, or rain shadow effects. Over long time scales, climate and weather in the Columbia Basin of Canada are controlled by global climate change, and natural climate variability that relate to changes in air mass source. Here, we use available data to evaluate the changes in historical climate across regions of the Canadian Columbia Basin, and evaluate the statistical relationship to Pacific Ocean Climate Indices and regional temperature changes.

Methods

We used data from 5 Environment Canada low elevation climate stations across the Canadian Columbia Basin; these are Golden, Revelstoke, Nakusp, Cranbrook, and Castlegar (Table 3.2.1). At each station we evaluated data completeness, temporal changes in temperature, rain, snow, and total precipitation. Since temperature and precipitation variables are influenced both by regional climate change, and by cyclic climate indices, we use both trend tests and a Regime Shift Indicator (RSI) test developed by Rodionov, (2004). This test allows us to determine statistical breakpoints in the datasets where a regime shift has occurred (i.e. a shift in the average value of the parameter in question). The RSI test is based on sequential analysis, where each new observation is used to test the null hypothesis, H_o: the existence of a regime shift. The test statistic is a two-tailed Student's T-test. This RSI test allows for the detection of regime shifts at a variety of time scales (decadal, multi-decadal, centennial, etc.), without any a priori knowledge of the timing of a particular regime shift (Rodionov 2004). We used the RSI test to evaluate changes in precipitation type and volume, and temperature at decadal time scales. Mean changes in annual and seasonal temperatures are derived using regression.

Because the datasets from actual climate stations in the CBTR are incomplete, we evaluate the data from ClimateBC for each of the five stations listed above, and for high elevation sites (>1900m) in each of the five statistical hydrologic regions (Table 3.2.2, Figure 3.2.1). ClimateBC uses the Parameter Elevation Regression Independent Slopes Model PRISM; PRISM produces spatial climate data in complex terrains by incorporating digital elevation models and has the capacity to account for elevation effects such as rain shadows and temperature inversions (Wang et al. 2006, 2012). ClimateBC calculates climate variables based on latitude, longitude, and elevation, and the results have a fairly good agreement with available weather station records to temperature (r^2 0.75-0.95) and fall precipitation (r^2 0.64-0.85), though historical extremes are not well captured. We compare the results to the dataset produced by Rodenhuis (2007) that also used PRISM at a larger spatial scale (50 km^2) to interpolate climate changes across British Columbia.

Since there is no single climate index that would completely describe the variability in moisture delivery to the Columbia Basin, in addition to the established relationships with the PDO and ENSO, we examined the statistical relationships between rain, snow, and total precipitation against the following Pacific Ocean Climate indices; East Pacific North Pacific Oscillation, the Western Pacific Index, Western Hemisphere Warm Pool, Aleutian Low, North Pacific Pattern, and the Northern Oscillation Index. The effects of Climate Indices on distal regions can lag by several months. Therefore, we compared regression analysis with monthly lag time for 1 month to 12 months for the weather variables listed above (and stream data). Historical data for all climate Indices and average annual global temperature were downloaded from the National Oceanic and Atmospheric Administration (NOAA) online Climate and Weather Data resource (NOAA 2013a). All climate indices are available from 1900-2011.

Results

Climate and Weather Changes (1900-2011)

Temperature

The most complete climate records were available for Golden, Revelstoke, and Cranbrook (Table 3.2.1). Using ClimateBC data mean average temperature increases ranged from ~1.0°C in the Golden, to 1.6°C in Cranbrook (Table 3.2.3). In all ten climate stations, temperature increases were greater for mid-winter months (December- February), and mid-summer months (June-Aug), and lowest through the fall months (September – November). Using climate station data, temperature regime shifts were detected at multiple years (Figures 3.2.2-3.2.4). Both Golden and Revelstoke indicated regime shifts at 1938 and 1987 at $p<0.001$, while Cranbrook indicated regime shifts at 1958, $p<0.05$ and 1986, $p<0.001$. We could not perform the RSI analysis for Environment Canada data at Nakusp and Castlegar due to incomplete datasets; however, performing the test using the ClimateBC data indicates regime shifts in 1938 and 1986 at $p<0.01$ (Figure 3.5-3.6).

The interpolated dataset form PCIC indicates mean annual temperatures increased by 1 to 1.5^{0}C across much the Columbia Basin, with more warming in the southern areas by 1.5 to 2^{0}C (Figure 3.2.7). PCIC data also indicate significant increases in the annual minimum temperature ranging from +1 to +2.5^{0}C across BC and in the Columbia Basin (Figure 3.2.8). Trends in the annual maximum were lower across BC ranging from +0.6 to +1.5^{0}C, but significant in the Columbia Basin with annual maximum temperatures increases of +1.3^{0}C per century (Figure 3.2.9). At a higher resolution, ClimateBC data shows regional temperature changes since 1970 (Figure 3.2.10).

Table 3.2.1 Climate stations used in this analysis including data completeness form 1900 to present.

Station Name	Latitude	Longitude	masl	Years Available Temperature	Years Available Precipitation
Golden	51 17 54	116 58 45	785	n=99 (1903-2007)	n=94 (1903-2006)
Revelstoke	50 58 00	118 11 00	445	n=94 (1903-2005)	n=88 (1899-1994)
Cranbrook	49 36 44	115 46 55	940	n=99(1901-2010)	n=91 (1909-2010)
Nakusp	50 15 59	117 48 46	512	n=51(112-1922,1966-2005)	n=39 (1913-1922,1966-1988)
Castlegar	49 17 46	117 37 57	496	n=51 (1917-1926,1966-2006)	n=51 (1917-1927,1938-1977)

Table 3.2.2 ClimateBC stations used in this analysis.

ClimateBC Station Region	Station Name	Latitude	Longitude	masl	ClimateBC High Elevation Station Name	Latitude	Longitude	masl
Upper East Columbia	Golden	51.29833	-116.979	789	Mt. Clemenceau	52.24027	-117.96	2178
Upper West Columbia	Revelstoke	50.96667	-118.183	444	Schrund Peak	51.31169	-118.529	2686
East Columbia	Cranbrook	49.61222	-115.782	940	Nautilus Mountain	50.92002	-117.269	1898
West Columbia	Nakusp	50.26639	-117.813	512	Mt. Harrison	50.11271	-115.161	2297
Lower Columbia	Castlegar	49.29611	-117.633	496	Mt. Plewman	49.16204	-117.895	2193

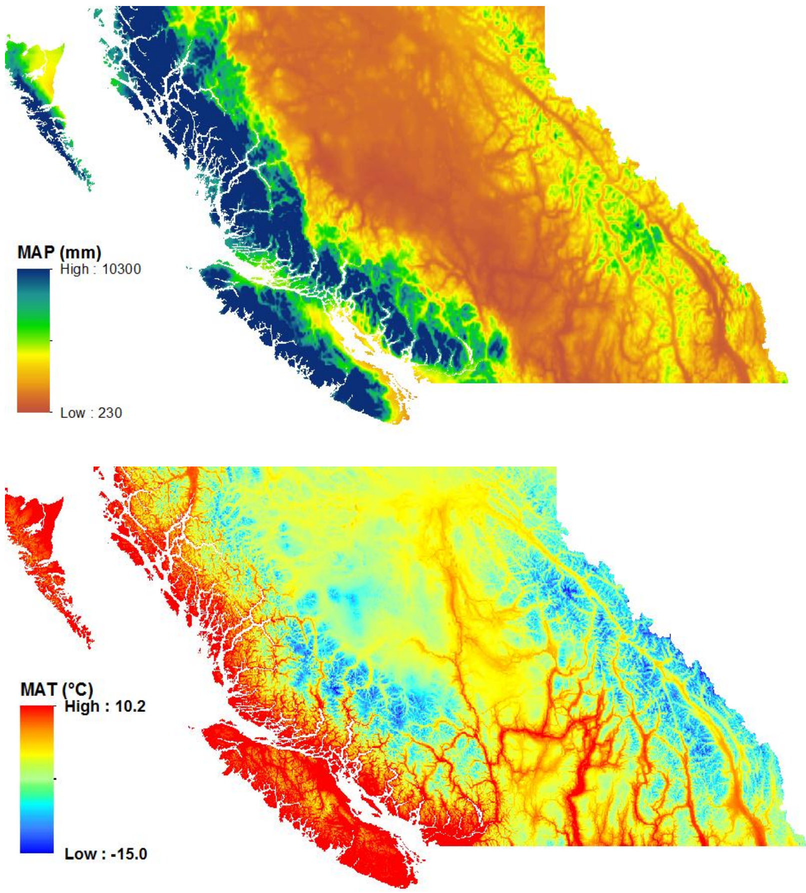


Figure 3.2.1 ClimateBC Normals from 1961-1990. MAP = Mean Annual Precipitation, MAT= Mean Annual Temperature.

Table 3.2.3 Mean changes in temperature at both annual and seasonal time scales for ClimateBC data, changes in temperature for station data are shown in brackets. Stars indicate trend significance with * p<0.01,p<0.0.5, *** p<0.001**

Station Name	Mean Annual Temperature Change(°C)	Winter (Dec-Feb) (°C)	Spring (Mar-May) (°C)	Summer (Jun-Aug) (°C)	Fall (Sept-Nov) (°C)
Golden	1.1***(1.86)	2.15***	1.1***	0.71***	0.41
Revelstoke	1.21***(1.64)	2.22***	1.05***	0.99***	0.65*
Nakusp	1.17***	2.09***	0.97***	1.05***	0.62*
Cranbrook	1.59***(1.72)	2.27***	1.44***	1.88**	0.80*
Castlegar	1.26***	2.18***	1.07***	1.10***	0.65**
Mt. Clemenceau	1.18***	2.29***	1.17***	0.91***	0.43
Schrund Peak	1.21***	2.24***	0.99***	0.98***	0.59*
Nautilus Mountain	1.17***	2.16***	1.08***	0.85***	0.57
Mt. Harrison	1.36***	1.87***	1.20***	1.27***	0.39
Mt. Plewman	1.14***	2.21***	0.96***	0.87***	0.57*

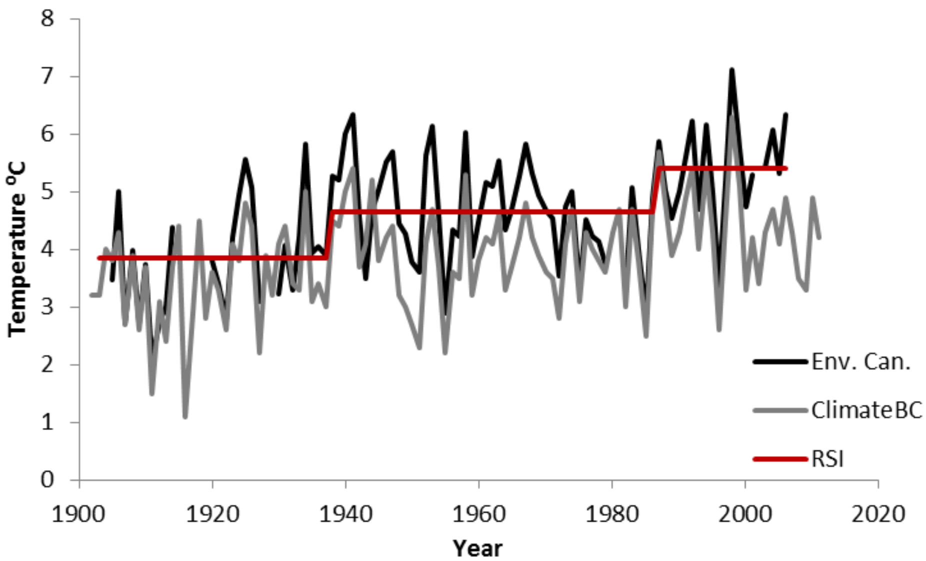


Figure 3.2.2 Mean annual temperature at Golden BC. The red line indicates regime shifts as detected by the RSI. Significant increases in temperature occur in 1938 (*p*<0.001), and in 1987 (*p*<0.005). The average temperature increased by 0.76°C form pre- to post-1987.

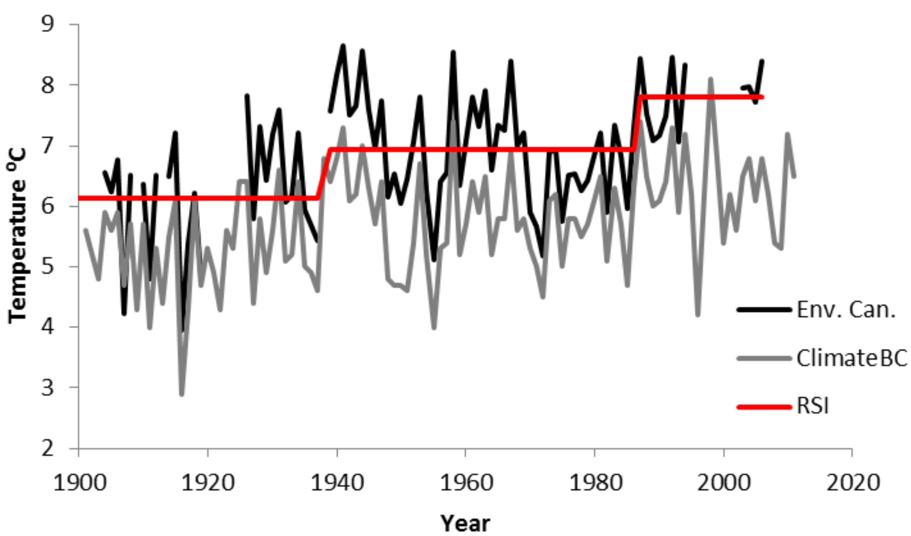


Figure 3.2.3 Mean annual temperature at Revelstoke BC. The red line indicates regime shifts as detected by the RSI. Significant increases in temperature occur in 1939(*p*<0.001), and in 1987 (*p*<0.001). The average temperature increased by 0.86°C form pre- to post-1987.

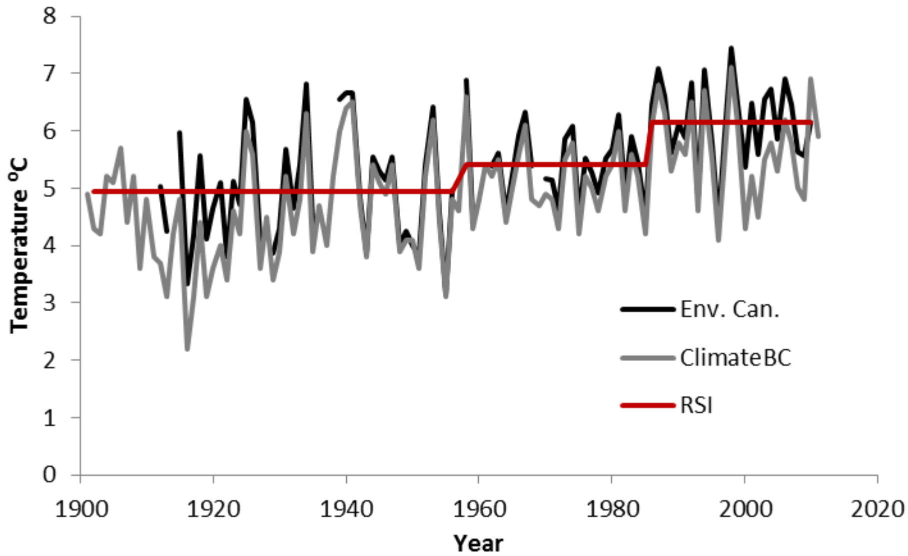


Figure 3.2.4 Mean annual temperature at Cranbrook BC. The red line indicates regime shifts as detected by the RSI. Significant increases in temperature occur in 1958 (*p*<0.05), and in 1986 (*p*<0.0005). The average temperature increased by 0.74°C form pre- to post-1986.

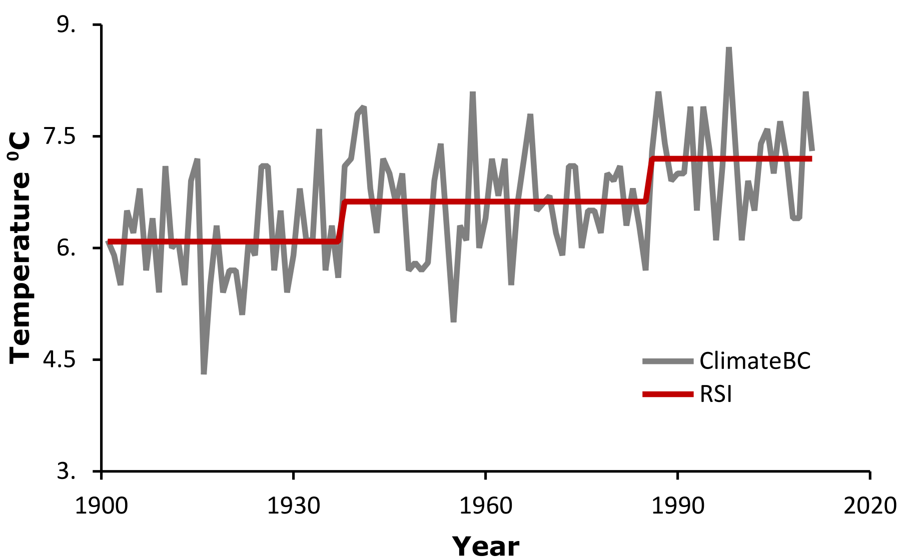


Figure 3.2.5 Mean annual temperature at Castlegar BC. The red line indicates regime shifts as detected by the RSI. Significant temperature increases occur in 1938 (*p*<0.001), and in 1986 (*p*<0.001). The average temperature increased by 0.57°C form pre- to post-1986.

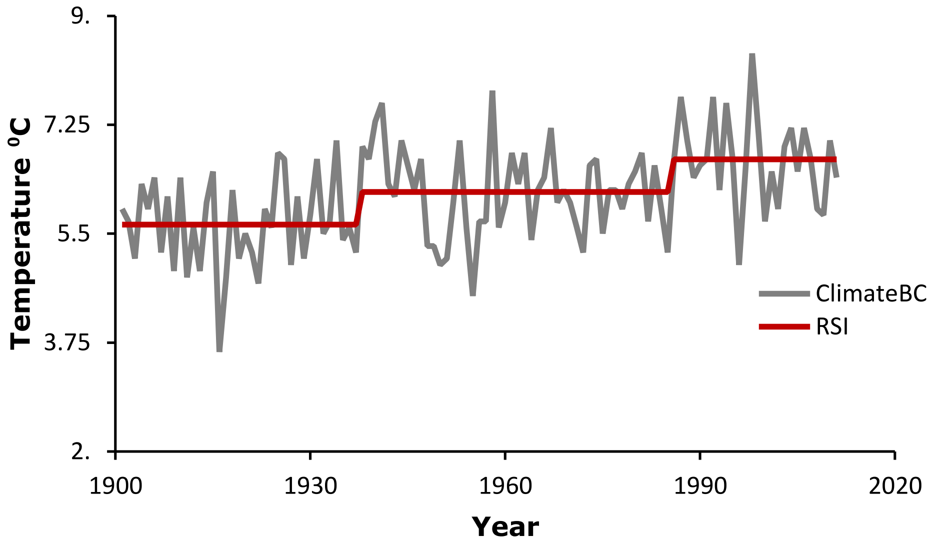


Figure 3.2.6 Mean annual temperature at Nakusp BC. The red line indicates regime shifts as detected by the RSI. Significant temperature increases occur in 1938 (p<0.001), and in 1986 (p<0.005). The average temperature increased by 0.52°C form pre- to post-1986.

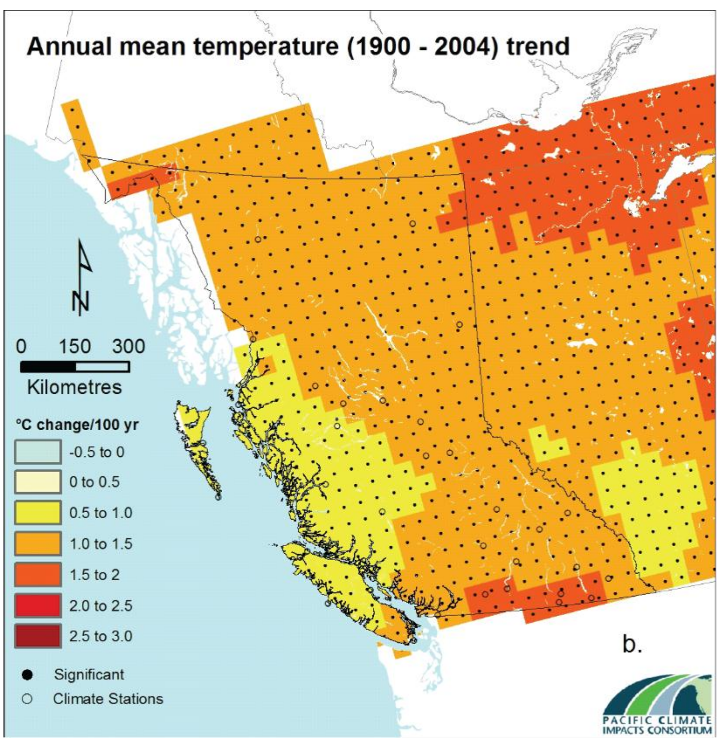


Figure 3.2.7 Reproduced from (Rodenhuis 2007). Interpolated mean annual temperature changes in BC from 1900-2004.

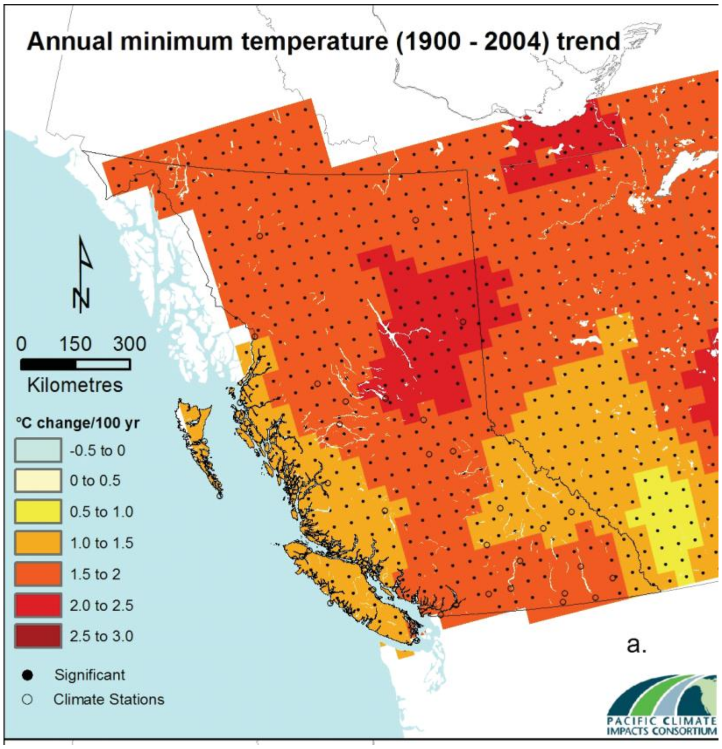


Figure 3.2.8 Reproduced from (Rodenhuis 2007). Interpolated mean minimum temperature changes in BC from 1900-2004.

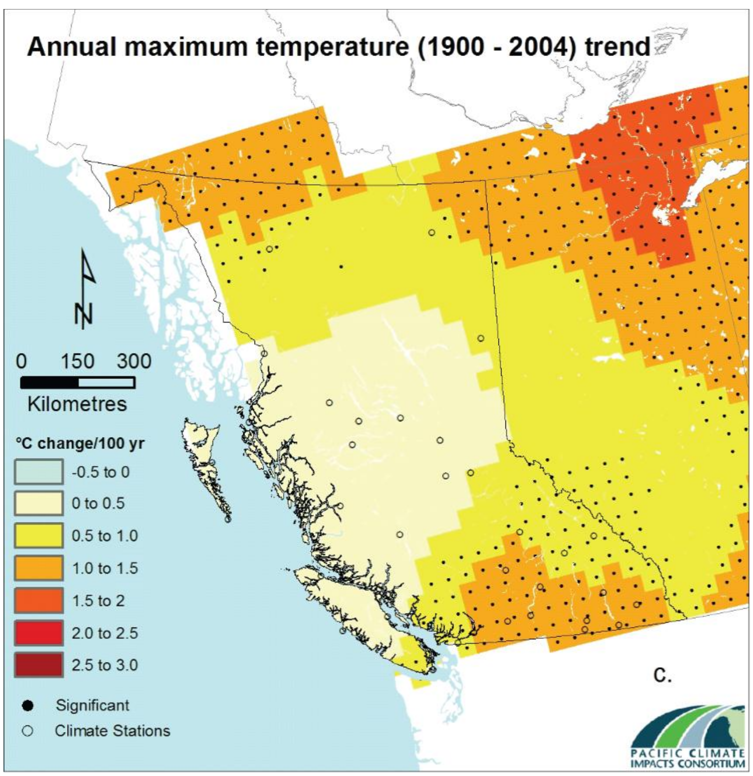


Figure 3.2.9 Reproduced from (Rodenhuis 2007). Interpolated mean maximum temperature changes in BC from 1900-2004.

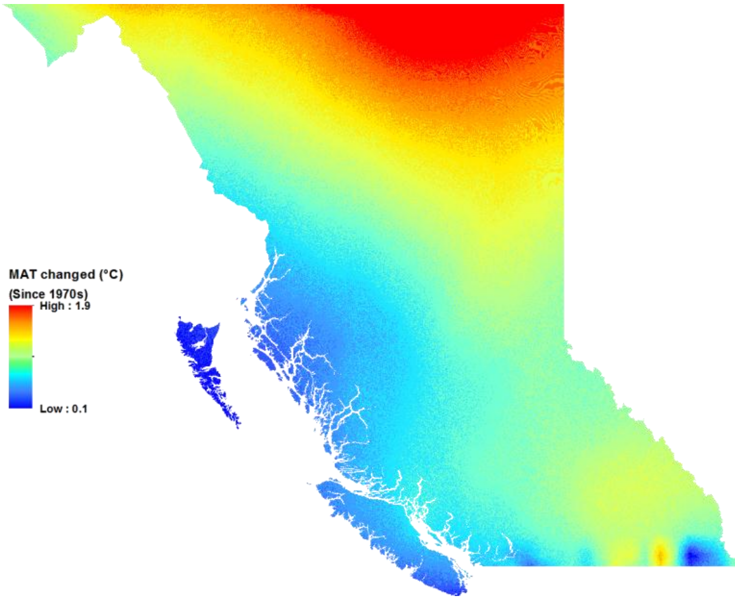


Figure 3.2.10 ClimateBC results for changes in temperature from 1970 to the 2001-2009 time period (Wang 2012).

Precipitation

Regression analysis of ClimateBC data indicate that total annual precipitation increased through the 20th century (Table 3.2.3). Only Golden and Cranbrook have precipitation data that extend into the 2000's. Total annual precipitation data from Golden indicate an increase of 21 mm (p=0.48) through the 1903-2006 period, contrasting the ClimateBC data which indicate a much larger increase, primarily due to the 2010 and 2011 precipitation years. Data from Cranbrook extends from 1909-2010 and shows a non-significant declining trend, also contrasting the ClimateBC data for the area. Regime shifts analysis of measured data indicate declines in total annual precipitation in 2000 for Golden are not significant (Figure 3.2.11), and in 1973 in Revelstoke, p<0.001 (Figure 3.2.11). No regime shifts were detected for annual precipitation in Cranbrook (Figure 3.12). Using ClimateBC data for Castlegar and Naksup we find a significant increase in 1945 and 1953 respectively, p<0.001, and in 2000, p<0.05 (Figure 3.2.13-3.2.14). The interpolated results found by Rodenhuis et al. (2007) indicate 10-30% increases in annual precipitation for the Columbia Basin Region from 1900-2004 (Figure 3.2.15).

Total snowfall showed significant declines in Golden from the late 1970's, p< 0.01 (Figure 3.2.16). At Revelstoke, there was a significant increase in snow fall in 1946, p<0.001, and a significant decrease in 1985, p<0.05 (Figure 3.2.17). Similar results were found at the Cranbrook station with a significant increase in 1950 and a significant decrease in 1976, p<0.05 (Figure 3.18). ClimateBC results for both Castlegar and Nakusp show increases in 1949 and 1947 respectively and decreases in 1976 and 1983 respectively p<0.001 (Figure 3.2.19-3.2.20). An increase in snow fall in Castelgar from 2010 was not significant (p=0.33). The interpolated data from PCIC show little to no change in the northern Columbia Basin regions, with increases in winter precipitation in the southern reaches by 10-30% (Figure 3.2.21). The total precipitation falling as rain significantly increased in 1976 in Golden (Figure 3.2.22), and in 1978 in Cranbrook (Figure 3.2.24). ClimateBC data from Castlegar show an increase in the late 1950's, followed by a decrease in 2007 (Figure 3.2.25). Climate BC data from Nakusp shows increases from the

late 1950's, and in 1980, followed by a decline in 2000 (Figure 3.2.26). Interpolated data from PCIC show increases in spring precipitation by 0-40% in various regions of the Columbia Basin (Figure 3.2.27), and increases in summer precipitation by 10-40% in various regions of the Columbia Basin (Figure 3.2.28); fall precipitation ranges from -5% to +30% across the basin (Figure 3.2.29). The proportion of precipitation falling as rain through the winter months (December –February) has significantly increased in Nakusp (p<0.005), and Castlegar (p<0.05).

Table 3.2.4 Mean changes in precipitation at both annual and seasonal time scales for ClimateBC data. Stars indicate trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001**

Station Name	Mean Annual Precipitation Change (mm)	Winter (Dec-Feb) (mm)	Spring (Mar-May) (mm)	Summer (Jun-Aug) (mm)	Fall (Sept-Nov) (mm)
Golden	66***	3	12**	45***	6.5
Revelstoke	142***	35.5	29***	63.5***	14
Nakusp	219***	58**	48***	84***	30
Cranbrook	38**	3	16***	18**	1
Castlegar	122***	25	42***	44***	11
Mt. Clemenceau	134*	3	47***	104***	-20
Schrund Peak	290***	56	56***	132***	46
Nautilus Mountain	250***	55	60***	123***	11
Mt. Harrison	101*	31	47**	19	4
Mt. Plewman	152***	30	62***	50***	10

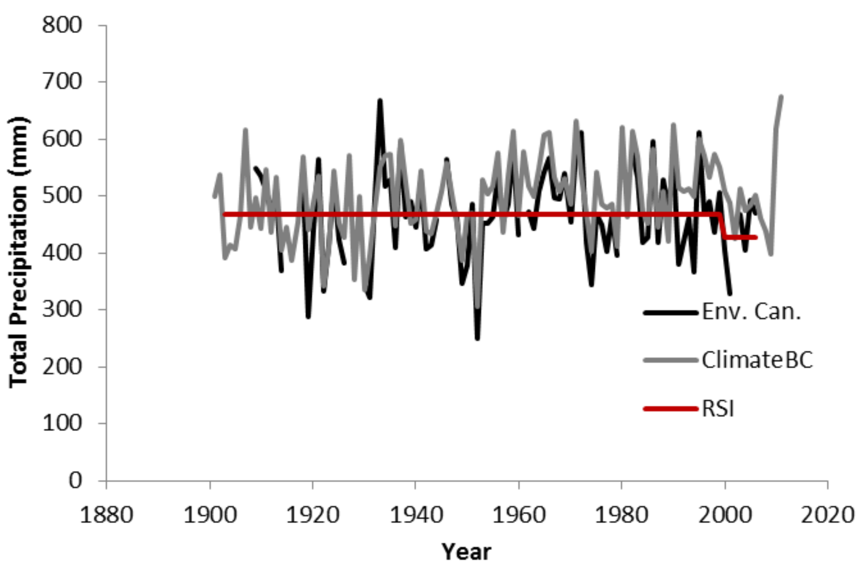


Figure 3.2.11 Mean annual precipitation at Golden BC from 1903-2006. The red line indicates regime shifts as detected by the RSI. A decline in average precipitation around the year 2000 was not significant (*p*=0.19).

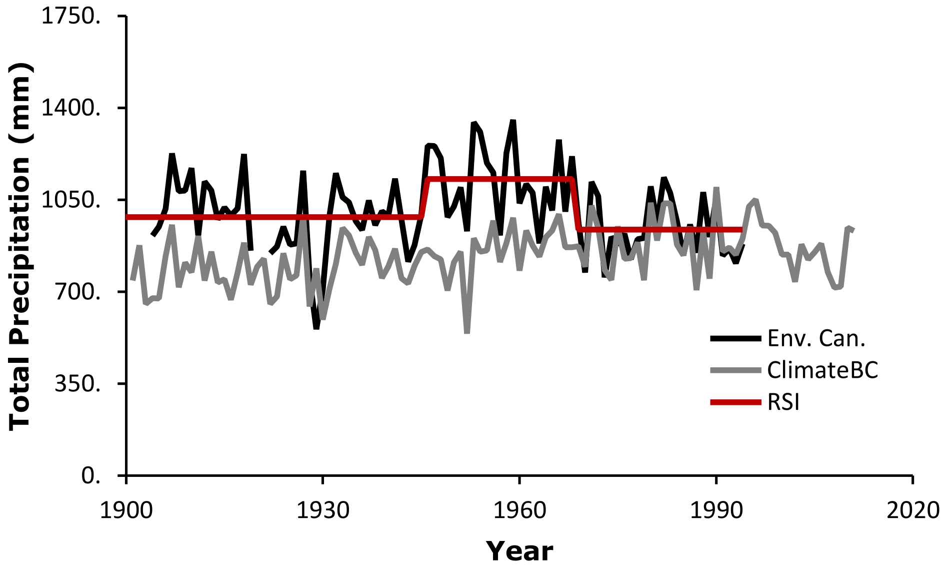


Figure 3.2.12 Mean annual precipitation at Revelstoke BC. The red line indicates regime shifts as detected by the RSI. A significant increase occurs in 1946 (*p*<0.001), and a significant decrease in 1969 (*p*<0.0001).

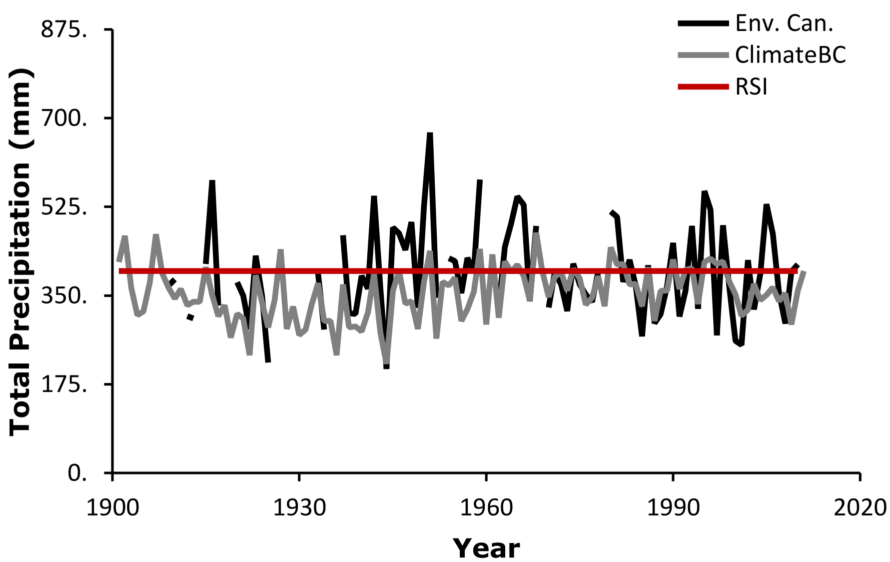


Figure 3.2.13 Mean annual precipitation at Cranbrook BC. The red line indicates regime shifts as detected by the RSI. No significant changes in the mean have occurred.

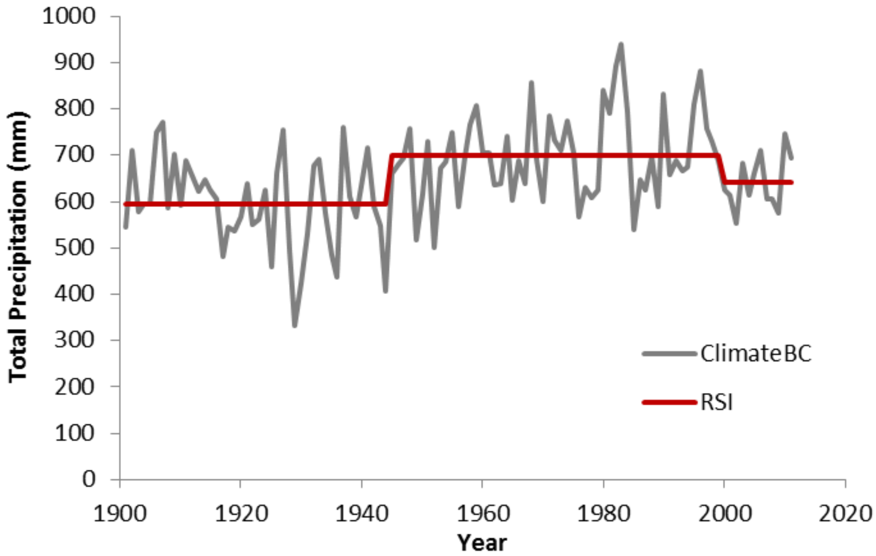


Figure 3.2.14 Mean annual precipitation at Castlegar BC. The red line indicates regime shifts as detected by the RSI. A significant increase occurred in 1945(*p*<0.0001), followed by a significant decrease in 2000 (*p*<0.01).

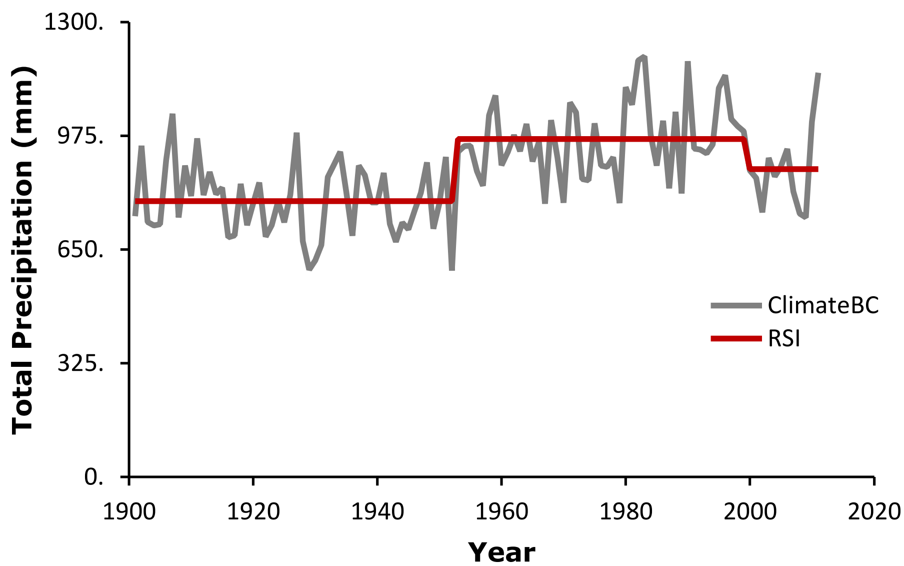


Figure 3.2.15 Mean annual precipitation at Nakusp BC. The red line indicates regime shifts as detected by the RSI. A significant increase occurred in 1953(*p*<0.0001), followed by a significant decrease in 2000 (*p*<0.05).

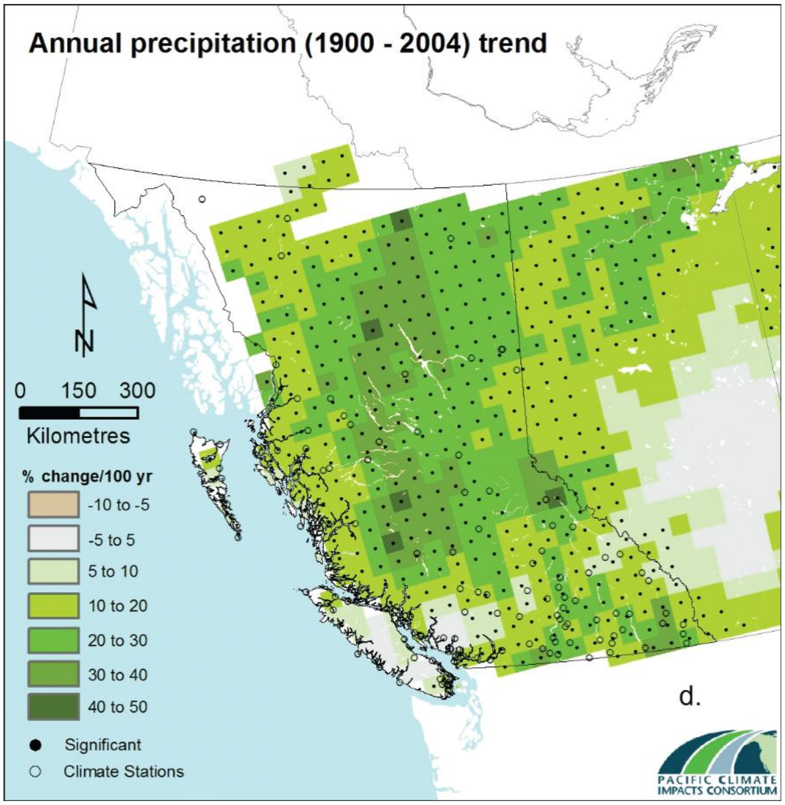


Figure 3.2.16 Reproduced from (Rodenhuis 2007). Interpolated mean annual precipitation in BC from 1900-2004.

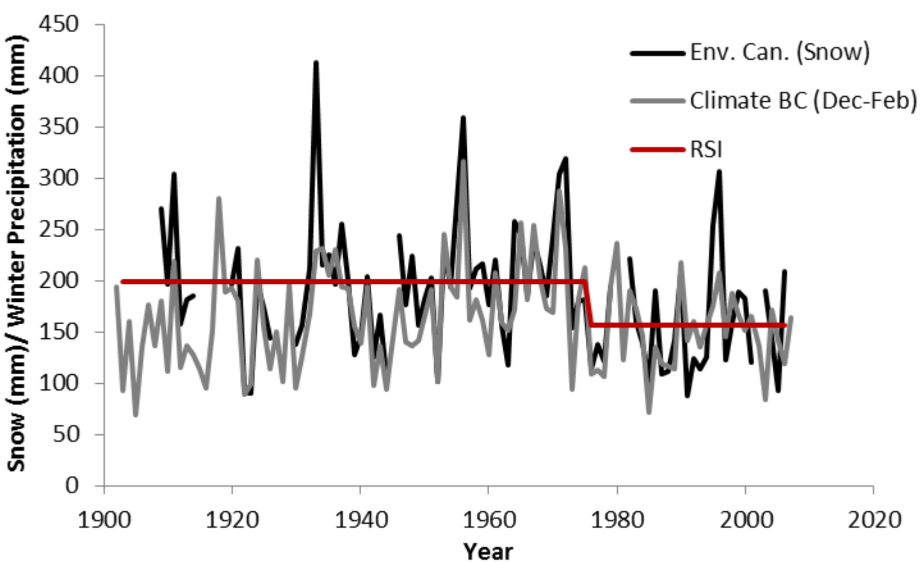


Figure 3.2.17 Winter precipitation from ClimateBC (December through February) and snowfall recorded at Golden BC. A significant decrease in snowfall occurred in 1976 (p<0.005).

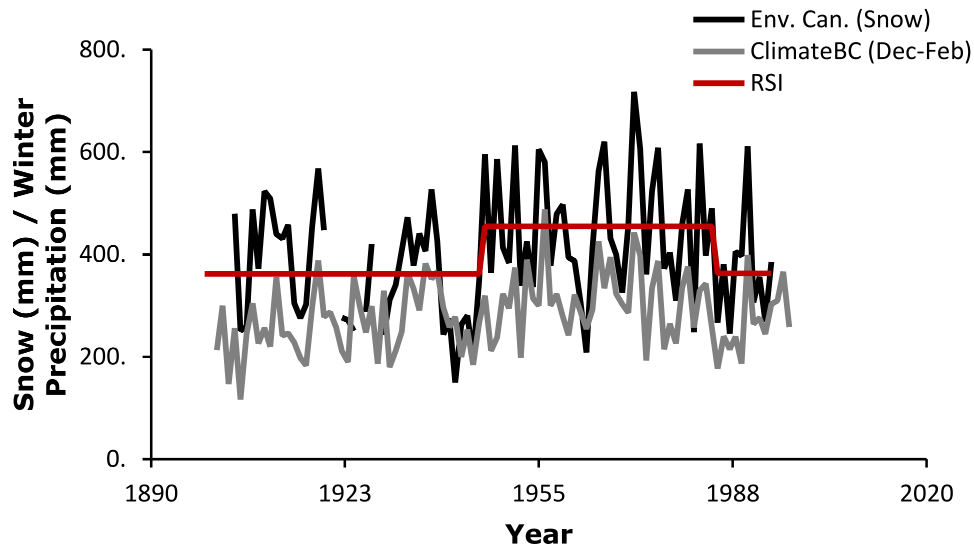


Figure 3.2.18 Winter precipitation from ClimateBC (December through February) and snowfall recorded at Revelstoke BC. Snowfall data from Revelstoke BC indicate an increase in 1946 (p<0.001), followed by a decline in 1969 (p<0.0001). Note that ClimateBC data does not distinguish between precipitation falling as rain or snow, nor does it include snowfall in the spring months.

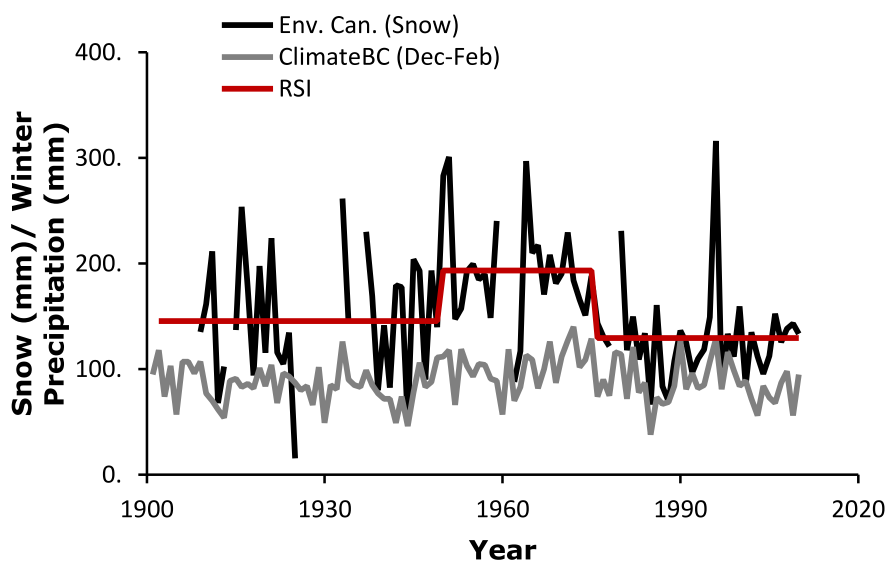


Figure 3.2.19 Winter precipitation from ClimateBC (December through February) and snowfall recorded at Cranbrook BC. Snowfall data from Cranbrook BC indicate an increase in 1950 (p<0.005), followed by a decline in 1976 (p<0.0001). Note that ClimateBC data does not distinguish between precipitation falling as rain or snow, nor does it include snowfall in the spring months.

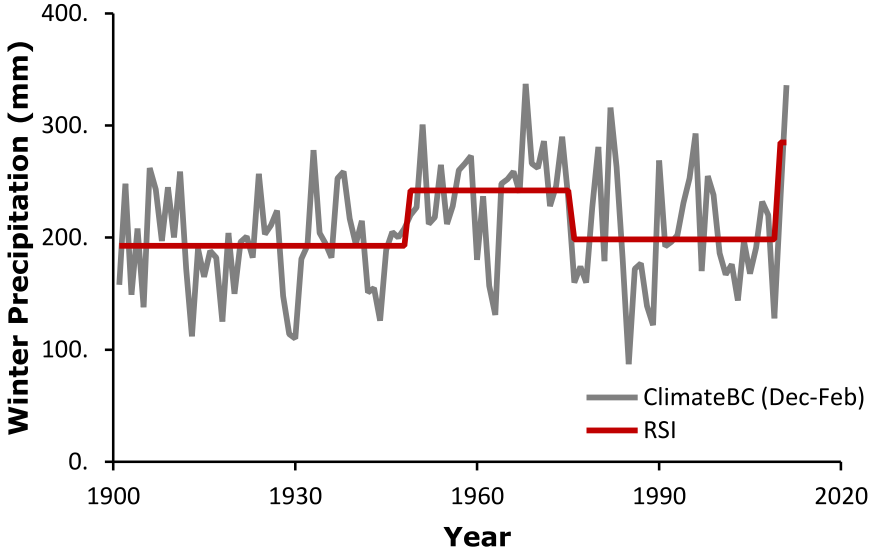


Figure 3.2.20 Winter precipitation from ClimateBC (December through February) from Castlegar BC. A significant increase in winter precipitation occured in 1949 (*p*<0.0001), followed by a decrease in 1976 (*p*<0.001). The increase noted from 2010 was not significant (*p*=0.33).

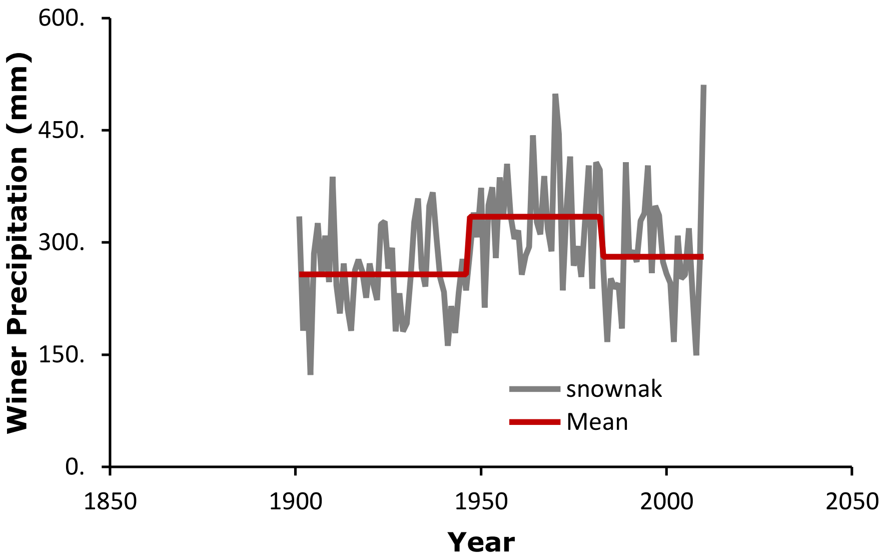


Figure 3.2.21 Winter precipitation from ClimateBC (December through February) from Nakusp BC. A significant increase in winter precipitation occured in 1947 (*p*<0.0001), followed by a decrease in 1983 (*p*<0.005).

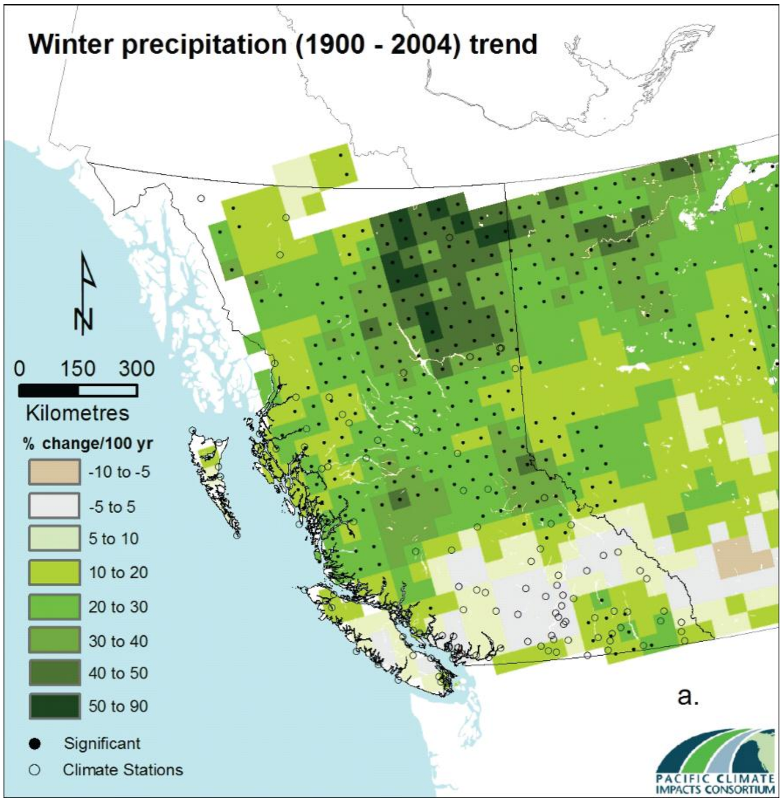


Figure 3.2.22 Reproduced from (Rodenhuis 2007). Interpolated winter precipitation in BC from 1900-2004.

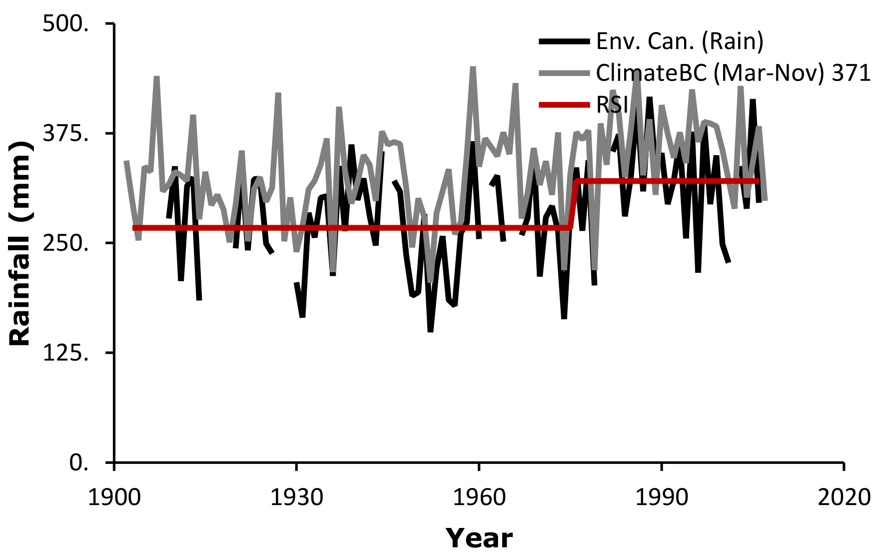


Figure 3.2.23 Total precipitation falling as rain in Golden BC and March through November precipitation from ClimateBC. A significant increase in precipitation falling as rain occurred in 1976 (*p*<0.0002).

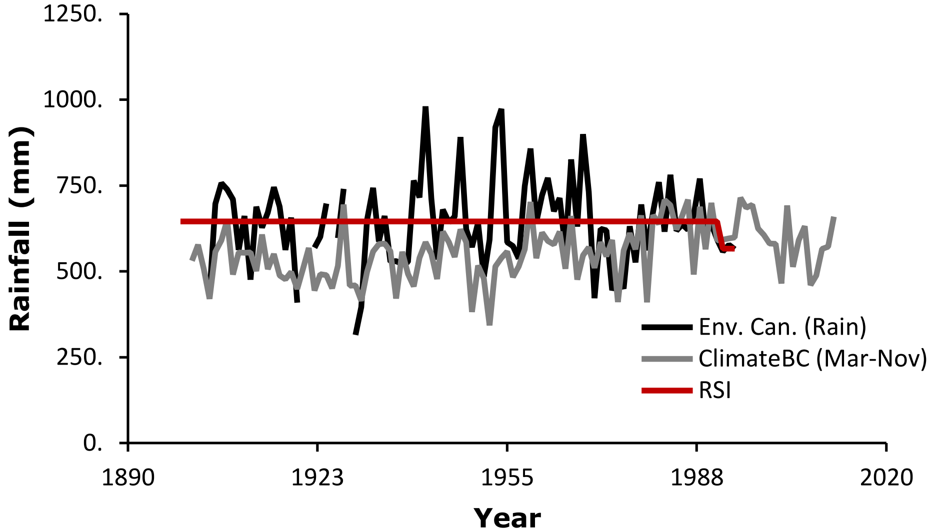


Figure 3.2.24 Total precipitation falling as rain in Revelstoke BC and March through November precipitation from ClimateBC. A significant decrease in precipitation falling as rain occurred in 1992 (*p*<0.0002).

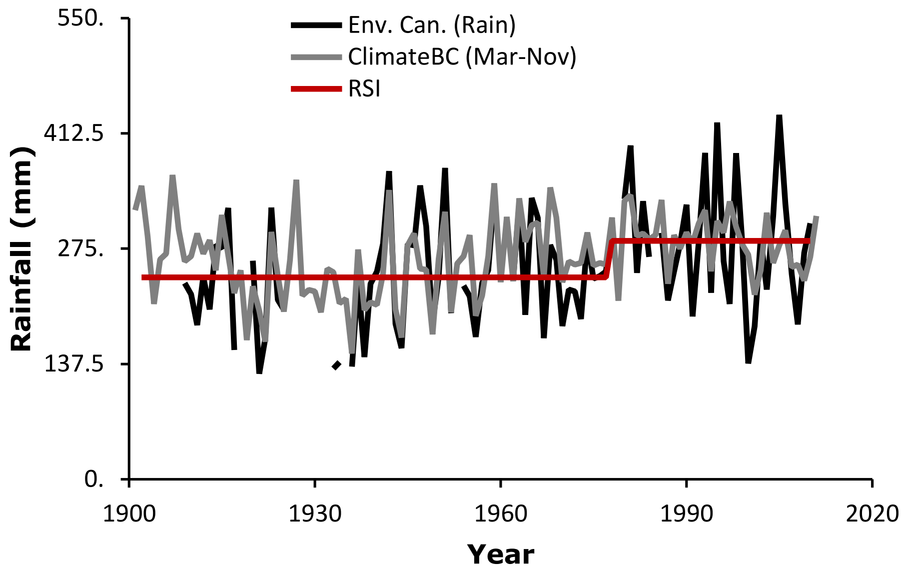


Figure 3.2.25 Total precipitation falling as rain in Cranbrook BC and March through November precipitation from ClimateBC. A significant increase in precipitation falling as rain occurred in 1978 (*p*<0.001).

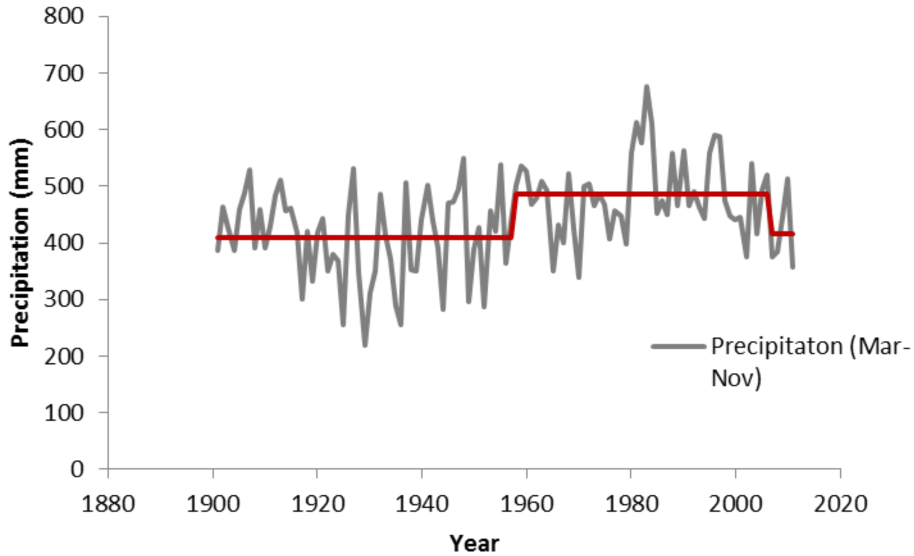


Figure 3.2.26 Total precipitation from March through November at Castlegar from ClimateBC. A significant increase in precipitation through these months occurred in 1958 (p<0.0001), followed by a decrease in 2007 (p<0.1).

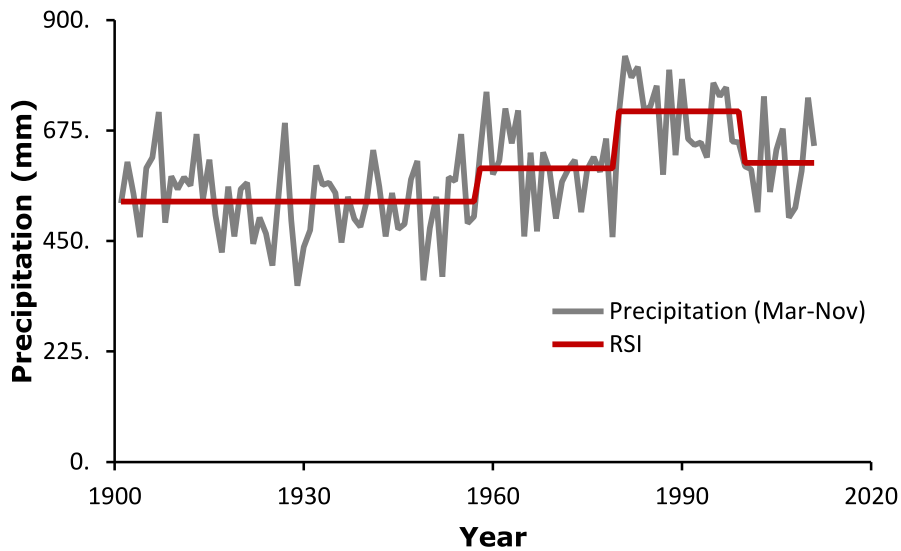


Figure 3.2.27 Total precipitation from March through November at Nakusp from ClimateBC. A significant increase in precipitation through these months occurred in 1958 (p<0.005), 1980 (p<0.0001), and a decrease in 2000 (p<0.005).

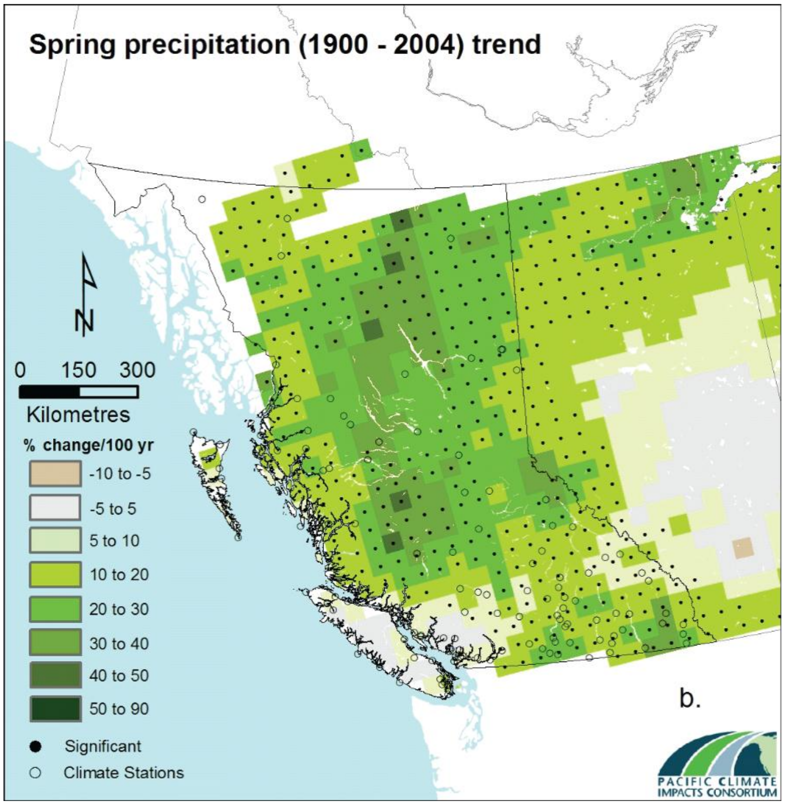


Figure 3.2.28 Reproduced from (Rodenhuis 2007). Interpolated spring precipitation in BC from 1900-2004.

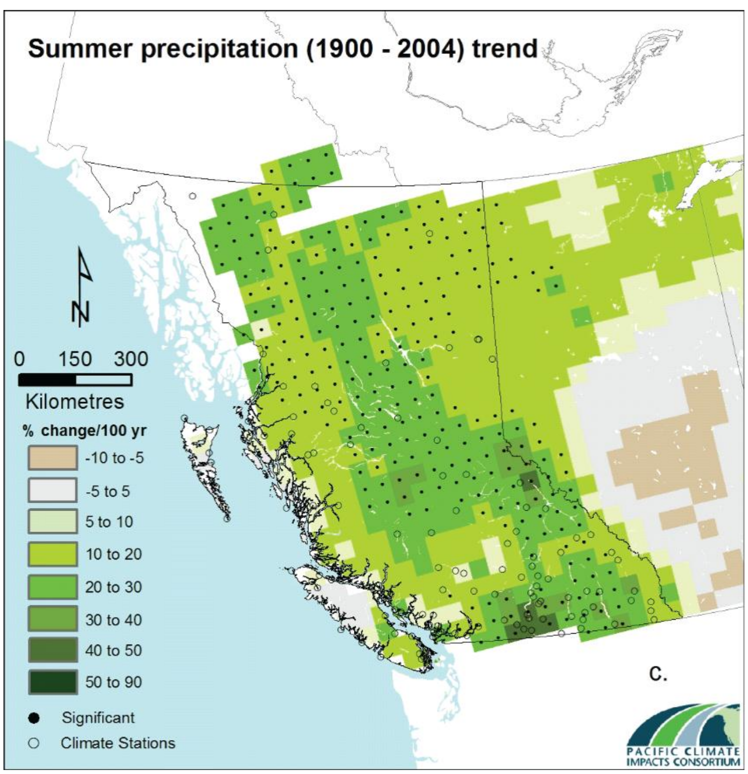


Figure 3.2.29 Reproduced from (Rodenhuis 2007). Interpolated summer precipitation in BC from 1900-2004.

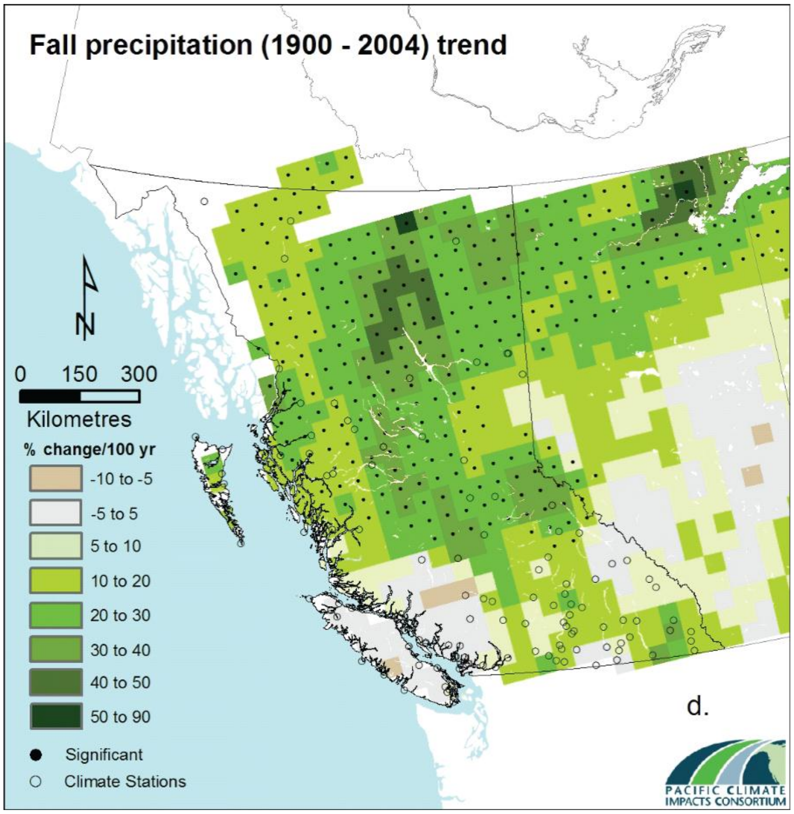


Figure 3.2.30 Reproduced from (Rodenhuis 2007). Interpolated fall precipitation in BC from 1900-2004.

Relationship to Climate Indices

Similar to other studies, we found that the PDO and ENSO explained a significant amount of the variation in precipitation across the Columbia Basin (Table 3.2.5). Regression analysis indicated that the Northern Oscillation Index (NOI) also significantly explains moisture delivery to the Columbia Basin. This is likely because the NOI may be effective at representing inter-annual to decadal variability at extra-tropical latitudes because it reflects changes in the Northeast Pacific and therefore has a physical connection to climate in the Columbia (Schwing et al. 2002). The NOI is similar to the Southern Oscillation Index as a northern counterpart, but is larger in amplitude and highlights events not captured by the SOI (Schwing et al. 2002). We found a 6 month lag in the annual averages of the Climate Indices explained the highest amount of variation, the historical variation of all three climate indices are shown in Appendix 1.

We found both PDO and ENSO were positively and significantly correlated to rain ($p<0.05$) and to total precipitation ($p<0.05$) and negatively correlated to snow ($p<0.05$) in most regions of the Columbia. The NOI was significantly negatively correlated to rain ($p<0.05$) and total precipitation ($p<0.05$) in most regions. Increased rain and decreased snowfall coincided with the shift from the cool phase of the PDO to the warm phase of PDO. However, there was no subsequent increase in snowfall coinciding with the

recent shift to cool phase PDO in 1998, likely due to a significant increase in temperature throughout this period (Figures 3.2.2-3.2.8).

Since 1998, a variety of biological and physical indicators of the Cool Phase PDO re-emerged (Chavez et al. 2003). There are several differences between the recent shift in 1998 and the conditions that characterized the previous Cool Phase. Since 1998, the PDO has not been consistently negative and some conditions in the North Pacific are inconsistent with the previous cool phase (Bond et al. 2003). Changes in marine conditions began in 1989, the mid-point of the Warm Phase, associated with the weakening of the Aleutian Low. A weak Aleutian Low is characteristic of a cool phase PDO (Rodionov et al. 2005). Though the absolute shift in the PDO to a cool phase may be unclear, it appears that from 1987/1988, there has been a general trajectory towards cooler, more negative PDO conditions (Appendix 1, Figure A1). The cause and or mechanisms of these phase shifts are beyond the scope of this analysis; however, the relationship, or change in relationships between these Climate Indices and moisture availability in the Columbia Basin is of interest here, both with respect to describing controls on moisture availability and the ability with which we can use these indicators to make predictions of future climate and discharge in the Columbia.

Because the most recent shift to a cold-phase PDO does not correspond to a concomitant shift to increased snowfall and rainfall, we examined the changes in the correlation coefficients to the PDO, ENSO, and NOI, for the full record, and pre- and post-1998. There are notable differences between the two time periods (Table 3.2.5). In particular, the strong negative relationships between the PDO/ENSO and snowfall are no longer evident post-1987/1988, and the relationship between PDO/NOI and total precipitation shifts from insignificantly negative to significantly positive. The relationship of the NOI to precipitation metrics does not change it's sign, though the relationships become stronger through time.

Table 3.2.5 The Average correlation coefficients for the relationship of climate indices to rainfall, snowfall, and total annual precipitation. The full record is shown for the five Environment Canada climate stations across the Columbia Basin of Canada, and the segregated time periods represent relationships to ClimateBC data as the measured datasets are incomplete. Stars indicate trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001. MAT=Mean Annual Temperature**

	Full			<1998			>1998		
	PDO	NOI	ENSO	PDO	NOI	ENSO	PDO	NOI	ENSO
Rain	0.20*	-0.26**	0.24**	0.25**	-0.21**	0.21*	0.41***	-0.55***	0.21
Snow	-0.23***	0.07	-0.25	-0.27**	0.06	-0.16	0.13	0.05	0.09
Total Precipitation	-0.04	-0.12	-0.02	0.04	-0.13	0.06	0.42***	-0.42***	0.22
Rain:Snow	0.27*	-0.13	0.24**	0.31***	-0.17	0.20*	0.09	-0.32***	0.04

Discussion

Increasing temperatures throughout the Columbia Basin Trust region in the last 100 years is clearly evident in the data and there are strong agreements between measured and interpolated and modelled data (Table 3.2.4, Figure 3.2.2-3.42.10). The average increase in temperature for the 5 ClimateBC station data that correspond to Environment Canada Stations ranged from 1.1-1.6^{0}C, though

the measured data indicated somewhat stronger increases ranging from 1.6-1.9^{0}C. There were notable step shifts - throughout the time series with significant increases occurring at all sites in the late 1980s (Figure 3.2.2-3.2.6). Trend analysis indicate that temperature increases were greatest in the southern areas (Cranbrook and Castlegar) (Table3.2.4), though the RSI test on the data indicated that the average increase since the late 1980s was greatest for Revelstoke, followed by Golden, and Cranbrook.

The increases in temperature have led to a shift in the type of precipitation, since the late 1970s and early 1980s there has been a clear shift to a decrease in precipitation falling as snow, and an increase in the proportion falling as rain. A large portion of this shift can be related to the transition from a cool to warm phase PDO in the late 1970s. However, the shift to a cool phase PDO in 1998 has not resulted in an increase in snowfall, and there has been an increase in the proportion of winter precipitation falling as rain in 2 of the 5 climate stations.

The changes in total precipitation across the CBTR were less clear. Trend analysis of ClimateBC and PCIC data indicated strong increases in precipitation from 1900-2004 throughout the basin with increases ranging from 10-30% (Table 3.2.4, Figures 3.2.22, 3.2.28-3.2.40), whereas Environment Canada measured data showed no significant trend through this time period. Because precipitation is heavily influenced by oscillating Pacific Ocean Climate Indices, the RSI test provides a more accurate representation of temporal changes in the CBTR. The RSI test results revealed a tendency toward increases in total precipitation form the 1940s to the 2000s, when a small decrease in precipitation occurred (Figures 3.2.11-3.2.15). The discrepancies between the interpolated and the measured data highlight the need for adequate measurement data across the diverse landscape of the CBTR. In general, annual precipitation increases through the last century were greatest in Nakusp, Revelstoke and Castlegar (Table 3.2.4).

Understanding historical climate variability across the CBTR is critical for regional scale projections of future climate change, which has important implications for a variety of economic and sustainable resources needs. The availability of historical annual temperature and precipitation data for the Columbia Basin Trust Regions is sparse, particularly in non-urban areas and in the northern reaches. Further, there are no long-term data sets for any stations at high elevations. This paucity of data not only makes it difficult to understand historical changes across the basin, but also makes it difficult to calibrate and validate regional climate and hydrologic projections.

The current Federal and Provincial networks are not adequate to detect regional changes in the complex terrain of BC. There are only 31 active annual climate stations in the CBTR, only seven above 2000m, and twelve have long enough records for evaluating historical change. With respect to station density, all regions are considerably below the WMO recommendation of one station per 100 to 250 km^2 area.

3.3.2 Summary of Data and Knowledge Gaps

In order to meet the perceived needs of various stakeholders there is an inadequate number of climate stations and data types. Identified data and knowledge gaps are as follows:

- Inadequate station density: the WMO recommended density is one station per 100 to 250 km^2, current densities by region are 8 to 76% of recommended density.
- Climate stations are biased towards low latitudes and altitudes, leading to regional uncertainties in climate parameters for northern and alpine regions in the CBTR.
- There is inadequate or no information on evaporation from the basin (M. Schnorbus, personal communication).
- Climate stations in the CBTR do not have the capacity to measure short-term precipitation intensity (10 minute precipitation).
- There are an inadequate number of climate stations above 2000 m.
- At least one study watershed exists in the region where climate data is available across elevation/climatological gradients, ideally this data would be available to other data-users.
- The region does not have the capacity to monitor regional atmospheric processes for the detection and mitigation of extreme precipitation events leading to floods (Peter Jordan, personal communication).
- There are severe problems with climate data accessibility.

3.3.3 Recommendations

Various factors will contribute to the amount of climate-related data in any given region, including population density, data collection objectives, financial support, and access to remote and difficult terrain. However, there are considerable financial, social, and economic implications of not having enough data, particularly in the CBTR where water resources are of paramount importance. To address the needs of the end-users, we recommend:

1) Avoid further reductions to the climate monitoring network of BC.
2) Support efforts to increase the availability of climate related data. This should include the incorporation of data collected by non-governmental organizations (e.g. Canadian Avalanche Association). All should be reported along with flags that indicate quality parameters and should be housed on a central registry maintained by the federal or provincial government.
3) Organize workshops and/or research networks including federal and provincial monitoring agencies, stakeholders, and researchers to identify the needs for climate and hydrometric projections, environmental effects analyses and monitoring, engineering, natural resource management, and resource allocation.
4) Work with federal, provincial, and local agencies to investigate opportunities to enhance the existing network through local citizen science groups, businesses, and/or collaborations with research groups.

a. Educate local communities on the socio-economic importance of climate monitoring and provide resources for the establishment of climate stations and maintenance, perhaps paired with Streamkeeper or CABIN sites.

b. Perform a climate data business review; for example Azar et al. {Azar, 2003 #625}. The end-goal is to engage end-users to collect data that meets their needs while contributing to the provincial and federal data base. For example, coordinate with the existing Canadian Avalanche Association database to make data available to all e-usiness-users. Additional opportunities likely exist with local farmers, land-owners, businesses, and industry to support/encourage the installation of automatic climate stations. An excellent example was initiated by Farmwest, where farmers were encouraged to install climate stations (with some financial support from provincial agencies), the station data is then used to provide useful information to farmers, including real-time evapotranspiration estimates and corn heat units in degree days.

c. Collaborate with research groups and universities to create opportunities for network growth. Once a station is established through research protocol, federal/provincial agencies may opt to provide maintenance support. For example, the establishment of the Parks Illecillewaet mass balance monitoring station was initiated through a short-term research project.

5) The above analyses highlight the discrepancies that may arise based on the method of analyses (regression versus regime shifts) as well as the time frame used, particularly due to the cyclic nature of the Pacific Climate modes. We recommend evaluating regime shifts for regionalized climate data at least every 5 years.

6) Assist provincial government with the identification and risk rating of drought, flood and debris flow hazards associated with changes in climate and hydrometrics. Enhance climate monitoring in these regions.

7) Prioritize and support data collections that have the highest potential for improving both climate and hydrologic projections in the region, including but not limited to

    a. Climate data collection at higher elevations

    b. Climate data collection at higher latitudes

    c. The establishment and study of climate gradients in all regions

    d. Paired studies of areas subject to and not subject to development (e.g. How temperature gradients change in and around water bodies in logged, forested areas regionally within the CBTR)

    e. Paleo-reconstructions of recent climate changes (lake core, tree-ring analyses)

8) Work with citizen science groups to incorporate measurements of ice on, ice off, and ice thickness in their protocols.

4.0 Surface Waters

4.1 Lakes and Reservoirs

Data availability and coverage

There is little data available through government sources on water quality in lakes and reservoirs within the CBTR. Paleolimnological analyses are available from Lake Windermere (1998), and water quality data from Kootenay Lake (1974) through the MoE report portal. More recently, MoE published a report on the water quality of Lake Windermere from an intensive 5-year sampling study (Neufeld 2010), and have reported on the success of the fertilization programs (Schindler et al. 2009; Schindler 2010). Following the MoE analysis of LW water quality, ongoing monitoring was taken over by the Lake Windermere Ambassadors at a reduced level. Because government funding for environmental monitoring programs is on the decline, citizen science groups in the CBTR have taken a leadership role in lake stewardship. LivingLakes Canada is a network of non-governmental associations that facilitates the monitoring, protection, and rehabilitation of lakes across the country. They are certified in CABIN protocols (for streams) and in DFO's Sensitive Habitat and Inventory Mapping (SHIM) procedure, which was conducted for both Windermere and Columbia Lakes. LivingLakes partners with Wildsight and the BC Lake Stewardship society (BCLSS), both of which are active in the Columbia Basin. The BCLSS initiated a monitoring program with multiple levels of complexity with respect to monitoring. In addition, they produced a LakeKeepers manual, which for considerable cost ($75+shipping) may be purchased as a guide for lakeshore residents and stewardship groups.

In conjunction with MoE, BCLSS operates the BC lake stewardship and monitoring program. BCLSS trains volunteers and provides equipment for 5 different levels of lake monitoring; more complex monitoring requires more knowledge and commitment for MoE staff, which may not always be available. Every three years, data is summarized into a report by BCLSS. The volunteer commitment is high, as 12 samples are required through the spring and summer.

In general there was very little information available on lakes, lake statuses, and historical changes in the CBTR. This is an unfortunate and substantial data and knowledge gap in evaluating water quality given the role that lakes play in watersheds. Lakes exist at the intersection of climatology, hydrology, geology, and ecology. Because lakes are extremely sensitive to their environment, they can be viewed as a fundamental ecological unit that respond over both short and long time scales. In addition, lake sediments are natural recorders of ecosystem change, making lakes particularly useful indicators of environmental health and change. As such, the CBTR could do with a comprehensive evaluation of contemporary and historical lake conditions with the potential development of useful tools for evaluating lake health, similar to that of the CABIN network.

4.1.1 Impoundments and channel modifications

The impacts of river impoundments on river hydrology largely affect the flow regime rather than water yield, though there remains a possibility that reservoirs may lose substantial amounts of water due to evaporative loss in a warmer climate. River impoundments affect the flow regime by changing the magnitude of discharge throughout the year as well as the frequency of high and low flow events. In the snowmelt-dominated catchments of the Columbia Basin, this translates to declining mean flows during peak months (spring) with higher flows during winter and late summer downstream of impoundments. These changes in flow regime can potentially mitigate the effects of climate change by redistributing water throughout the year to when it is needed downstream of hydrologic impoundments.

Impacts due to changing flow regimes are largely ecological and in the Columbia include changes in riparian habitat, stream food webs, disruption of fish life cycles, erosion, spawning and migration cues, unsuccessful recruitment of tree seedlings, and impacts on benthic invertebrates. However, building dams and moving communities upslope has to some decree increased flood and landslide hazard.

The construction of dams in the Columbia River Basin began in 1922 and continued until 1982. The inundation of over 100,000 hectares of land and the alteration of the natural flow regime clearly had remarkable and permanent ecosystem effects. One of the most tangible effects was the reorganization of landscape and habitat types. Prior to dam construction, Arrow and Whatson reservoirs were smaller, but existing lakes such as Kinbasket, Revelstoke, Koocanusa, Pend Oreille, and Spillimacheen were large forested rivers systems, and the Duncan Reservoir area was a mix of lakes, forests, and wetlands. The alteration of the landscape and flow regime through impoundments affects water quality directly through the alteration of thermal regimes, erosion and sedimentation, and nutrient dynamics, and, indirectly through changes in habit, biology, and aquatic-wetland-forest ecosystem interactions. A comprehensive overview of the ecological impacts of impoundments to both the terrestrial and aquatic environment is available through the Fish and Wildlife Compensation Program (Utzig and Schmidt 2011). It is, however, difficult to fully evaluate the environmental impacts as ecosystem data prior to dam construction is spotty and sparse.

Impoundments fundamentally alter a variety of natural ecosystem flows. They cause changes in the timing of water movement and discharge, which influences riparian and in-stream ecosystem function. This interruption of the natural flood affects geomorphic and seasonal processes that transfer material (e.g. sediments and nutrients) downstream and between the terrestrial and aquatic environment. These changes have the potential to create sediment, or contaminant, hotspots in upstream low flow regions where sediments may accumulate, or, may cause oligotrophication of downstream environments due to the sedimentation and trapping of nutrients upstream. An additional loss of nutrients may occur through the blockage of upstream migration of all fish species. For example, the Grand Coulee dam built in 1941 blocked what is estimated to be over one million spawning salmon. The combined effects of decreased nutrients and loss of spawning habitat resulted in a substantial

reduction in Kokanee population in Kootenay Lake and Arrow Reservoir. In an attempt to remedy the loss nutrient status, fertilization programs were initiated for Kootenay Lake (1991), and Arrow Reservoir (1998). Both programs are considered to be successful in the restoration of Kokanee populations (Schindler et al. 2009; Schindler 2010).

Reservoirs also fundamentally change the character of lake systems. In addition to the above, outflow is not always from the surface waters as would be in a natural lake. Further, natural lake and stream thermal regimes are disrupted. In a natural system water temperatures show marked temperature fluctuations in response to daily and seasonal changes, and the volume and source of water contributing to discharge. Reservoirs will tend to stabilize the thermal regime with cooler water in the summer and warmer water in the winter, which affects both the lacustrine environment and that of the outflowing streams. Because certain species have chronic and acute temperature thresholds for growth, survival, and reproduction the alteration of the thermal regime of streams and lakes will influence species composition. In addition, water temperatures will also influence the solubility of various compounds, nutrient fluxes and cycling. Though daily average temperature data is available for EC monitored steams, a comprehensive understanding of daily and annual changes to the thermal regime is not available to the wider scientific community.

There are still several uncertainties surrounding the effects of altered nutrient fluxes and species composition, as well as the combined effects of changed flow regime and nutrients. For example, within the Canadian Columbia Basin and other regions of western North America, there has been a recent proliferation of the native diatom *Didymosphenia geminate* ('rock snot'). Blooms of this species negatively affect other aquatic organisms by altering food quality and habitat and their presence diminishes aesthetic and recreation value. The reason for recent overgrowths is not well understood, but may be related to altered nutrient concentrations, UVR, temperature, flow regime, or a combination of the above (Ellwood and Whitton 2007; Kirkwood et al. 2007; Kilroy and Bothwell 2014).

A list of the water and ecosystem effects related to impoundments is provided by Utzig and Schmidt (2011) and reproduced here:

Definition of Footprint Impacts

These impacts would occur primarily as a result of inactive storage and construction of dam structures, and are largely irreversible. Some impacts are re-occurring but the causative agent is usually a one-time action or event. Any footprint impacts should be considered when reservoir is at full pool.

- Construction impacts (e.g. sediment, water quality) temporary events associated with building and construction
- Habitat loss from facilities or structures (e.g. habitat inundation by reservoir): includes loss of riparian area for LWD recruitment and permanent lotic - lentic habitat change and impact
- Permanent loss of upland and riparian terrestrial habitats within the full pool footprint and their associated impacts on biodiversity

- Fragmentation and loss of habitat connectivity at landscape scale
- Changes in the amount and spatial extent of aquatic-terrestrial species interactions due to loss of seasonal habitats, shifts in primary productivity or habitat fragmentation
- Nutrient or contaminant effects (e.g. trapping, downstream release, methylation) related to flow released from the reservoir
- Water quality in reservoir (e.g. temperature, TGP, DO) related to water quality within the water column of the reservoir
- Erosion, sediment transport, erosion and morphological change due to reservoir could include effects of interception of bed load and increased earth slides and instabilities caused by reservoir drawdowns
- Impacts to fish movement and migration often due to structures like dams or barriers exposed during reservoir drawdown
- Fish entrainment and loss of fish includes loss of fish from reservoir populations with the inability to return to natal areas resulting in a loss of fishing potential or damage to the population numbers, dynamics, etc.
- Ice regime impacts due to reservoir and effects on tributary systems and ice effects within the reservoir or due to the thermal action of the stored water
- Local hydrological effects increased snow or precipitation due to thermal effects of reservoir, evaporative water losses, long-term groundwater effects, greenhouse gas release, and cumulative effects from other uses (i.e. increased water withdrawal due to proximity to reservoir)

4.1.2 Data and Knowledge gaps

- A comprehensive inventory of contemporary lakes and their status
- A historical (paleo) understanding of the regional lakes and their conditions
- A comprehensive understanding of the changes in thermal regimes related to impoundments (and climate change)
- The influence of impoundments on nutrient fluxes downstream and species composition
- The combined effects of altered nutrient flux, flow regime, temperature, UVR, and climate change on the stream habitat and chemical cycling

4.1.3 Recommendations

- The combined effects of impoundments and other land-use changes on ecosystem services such as the preservation of biodiversity, and pollution control is difficult to determine because

information on pre-existing aquatic ecosystem conditions is limited. We therefore recommend supporting research establishing a comprehensive understanding of historical limnological conditions in the region.

- Because thermal regimes may be altered by impoundments, we recommend monitoring temperatures changes that are ecologically relevant. For example, freshwater fishes and insects repost to absolute temperatures as well as the summation of thermal units. So an ecologically relevant metric may be: the daily temperature distribution, frequency, duration of time a stream or lake is above or below a given temperature, and other summary statistics.

- Lake assessment tools should also be developed (as have been done for streams) to disentangle the effects of multiple stressors the lake ecosystems. This may include the definition of biological quality elements for lakes (population and morphology), as well as historical conditions and the timeframe of change. The pollution induced community tolerance approach is a possibility, but may require more expertise than CABIN for the analyses of plankton species composition, and/or life forms and cell sizes of diatoms (for example).

- Integrate data collected by various agencies in the CBTR. All should be reported along with flags that indicate quality parameters and should be housed on a central registry maintained by the federal or provincial government.

- Support the ongoing initiatives of citizen science groups to monitor lake status and investigate opportunities to enhance the existing network.

- Assist provincial government with the identification and risk rating of various lakes.

- Provide an easier/ or less costly access to the LakeKeepers manual for all lakeshore residents.

4.2 Streams and Rivers

Water Quantity Data Availability and Coverage

At present there are 51 active gauges on streams and reservoirs in the CBTR, providing information on 39 different streams. Eleven of the gauges are on regulated streams. Data is easily accessible through the Water Survey of Canada's website. Data contributions are from Federal, Provincial, American, and private sources including Environment Canada, Ministry of Environment, BC Hydro, Fortis, and the US Geological Survey. There are likely other sources of data from private sources, though this data was not easily accessible. Please see Phase 1 Part 1 and associated documents for more details. Based on the guidelines provided by the WMO (1981, 2008), gauge coverage ranges from 9 to 56% of the recommended density of one gauge per 300 km^2, and 16% to fully compliant of the minimum density of one gauge per 1000 km^2 (Table 4.1.1).

Table 4.1.1 Percent station covered for each region based on WMO guidelines. Ideal coverage is one station per 300 km^2, minimum density of one station per 1000 km^2.

	Upper East	Upper West	East	West	Lower
% of Ideal	9%	6%	24%	20%	56%
% of Minimum	30%	19%	78%	67%	187%

Table 4.1.2 shows the distribution of gauges by region and watershed area. There is a bias towards the measurement of streams on watersheds greater than 1000 km^2, and very little information on watersheds less than 50 km^2, and only one watershed less than 10 km^2. The lack of representation between different hydrometric, climate, and biogeography regions as well as watershed areas presents several water management related problems. There is an almost complete lack of representation from small watersheds, particularly in dry regions. These streams often have ephemeral flow, and are thus more sensitive to both drought and high intensity rainfall. Because the very nature of discharge in ephemeral streams is different than that of larger watersheds, it is not possible to use hydrometrics from larger watersheds to predict flow response in these streams. There is a general need for procedures that can estimate streamflow characteristics (annual/monthly discharge, peak flow, low flow) of ungauged watersheds for resource management (e.g. low flow requirements, BC Water Sustainability Act). Hydrometric regionalization and standardized discharge plots (isolines) can be created; however, data from representative streams and watershed area are required as scaling between watershed classes can be problematic (Church 1997). There are 38 hydrometric stations with more than 50 years of data and 12 with more than 75 years of data (Table 4.1.3).

Table 4.1.2 Stations by region and watershed area.

Hydrometric Station	Upper East	Upper West	East	West	Lower	Total
< 50 km^2	0	0	0	1	3	4
50-100km^2	1	0	0	2	3	6
100-500km^2	2	0	6	1	2	11
500-1000 km^2	1	1	1	1	0	4
>1000km^2	4	2	7	2	8	23
Total	8	3	14	7	16	**48**

Table 4.1.3 Stations by region and record length, includes inactive stations used in this study.

Length of Record (Years)	Upper East	Upper West	East	West	Lower	Total
<15	4	0	1	1	0	6
>15	16	11	19	10	32	88
>30	13	10	18	10	28	79
>50	3	3	8	4	20	38
>75	1	0	4	1	6	12

Water Quality Data Availability and Coverage

Physical environment and chemistry

Through government agencies and the Columbia Basin Watershed Network (CBWN) there are 22 streams monitored for chemical and physical parameters through some portion of the year with easily accessible data. Environment Canada's Water Quality monitoring program focuses on long-term monitoring for status and trends, while the Ministry of Environment focuses on water bodies of concern, and monitoring schemes are generally shorter in duration. Environment Canada (EC) has 14 active stations monitoring 8 streams (Table 4.1.4); only 4 of those are in watersheds smaller than 500 km^2. Data from Environment Canada (EC) begins in the late 1980s (at present 27 years of data), and in the mid 2000s from CBWN. Though there are no specific guidelines for stream station density, water quality is highly variable in both space and time leaving considerable spatial and temporal gaps in long-term and baseline data availability. The current scheme that focused on point source pollution and areas of interest leaves gaps related to evaluating changes in small ephemeral streams, and diffuse sources of contamination including that from the airshed (long travelled contaminants)({Daly, 2007 #546}), or the watershed from land-use, fires, etc. ({Binkley, 1993 #626}), or the stream itself from invasive and/or bloom forming species ({Kirkwood, 2007 #534}). Station density is particularly sparse in the northern and western regions of the CBTR.

Table 4.1.4 The number of active and inactive EC water quality station by region (as defined by the water quantity analyses, see appendix)

Water Quality Station	Upper East	Upper West	East	West	Lower	Total
Active	4	1	3		6	14
Inactive	3	1	3		3	10
Total	7	2	6	0	9	**24**

EC also maintains monitoring under the Chemical Management Plan for toxic substances in water, sediment, biota, and wastewaters. In the CBTR, 10 predator and 10 prey fish species are sampled in the Lower Columbia. In 2003 a study to evaluate pesticides in water bodies was initiated through Health Canada; there were likely some sites in the Columbia Basin, although data has not yet been made available to the public. Though the federal government has programs in place to measure a variety of toxic substances including pharmaceuticals, pesticides, mercury, and other 'emerging substances', southeastern BC is not well represented in these analyses despite the agriculture, industrial, and communities present in the region. In addition, the presence of glaciers and high elevation snowfall increases the potential for the presence of far-travelled cold condensation contaminants (see section 7.1).

Biomonitoring (Benthic Macroinvertebrates)

Both government agencies incorporate biomonitoring programs to evaluate water quality. The Canadian Aquatic Biomonitoring Network (CABIN) is maintained through Environment Canada, and the province also uses CABIN framework for its biological monitoring. Both government programs are reported on the CABIN network, which lists some 173 sites measuring 78 streams in the Columbia Basin, though the data is not available to the public or the larger scientific community and it is unclear at what frequency the streams are being monitored. The inaccessibility of the data to the general public and larger scientific community is inefficient and some time and effort should be directed towards solving this problem. The Columbia Basin Watershed Network (CBWN) uses the CABIN framework, and reports the 14 sites they monitor through their web portal (http://cbwn.ca/dev/water-quality-database/).

Biomonitoring in the CBTR is based on the reference-condition approach (RCA) where water quality is evaluated using stream benthic macroinvertebrate bioindicators (Gaber 2012). Because species are sensitive to various forms of pollution and ecosystem change, their presence or absence can be used to evaluate stream health against an unpolluted 'reference stream' of similar character. This system is advantageous for several reasons: it is scientifically defensible, cost-effective, and can incorporate data from citizen science community groups. The latter being important not only for generating data, but for the communities' involvement in the monitoring and protection of their own environment. Within the Columbia-Okanagan system there are 125 reference streams with five predictor variables including (latitude, longitude, % catchment with a slope less than 30%, stream depth and duration of ice cover)(Gaber 2012). The reference sites have been linked to the federal network (CABIN). Data are

collected at various timescales and used to monitor stream condition at sites of concern within the CBTR, and to make decisions for discharge permits by regional staff (Personal Communication Leon Gaber R.P. Bio MoE.). The program is in the initial operational stages, but is expected to be used to evaluate long-term trends in stream conditions relating to, for example, the presence of pollutants, land-use, insect outbreaks, fire, and climate. Due to the sensitivity of benthic macroinvertebrates, monitoring their species abundances can fill knowledge gaps on stream health where regular stream monitoring is not occurring. To ensure quality data from citizen science groups, MoE staff work with community groups such as Streamkeepers, or CBWN providing guidance and training. Since water resource MoE scientists are few, their time is at a premium and they cannot always be available to train and monitor the progress of citizen science groups. Additional challenges of this model in the mountainous region of the Columbia are the differences in species composition due strictly to elevation (Personal Communication, Jolene Ragget. R.P. Bio MoE.).

Government Reporting

Environment Canada examines their stream chemistry and physical parameter data for historical changes (trend analyses) and for any evidence of anthropogenic influence. The Ministry of Environment has produced comprehensive analyses on the water quality concerns from point and non-point sources with water quality objectives and recommendations for several regions in the CBTR including:

- Lower Columbia: Birchbank to US Border (last updated 2000)
- Lower Columbia: Hugh Keenleyside Dam to Birchbank (last updated 1992)
- Upper Columbia: Toby Creek to Spillimacheen (last updated 1985)
- Upper Columbia: Windermere Lake (last updated 2010)
- Upper Columbia: Columbia Lakes (last updated 1985)

Additional reports cover regional water quality analyses and objectives as well as trend analyses, impact assessments, plankton and fish assessments, and monitoring recommendations. Most of the water quality objectives (above) are out of date and new data has yet to be incorporated (Personal Communication, Jolene Ragget. R.P. Bio MoE.). In additional there are considerable spatial gaps in the monitoring network as well as a consistent reduction in the network, staff, and resources to maintain the program.

CREIMP has produced comprehensive reports on the water sediment, and habitat quality objectives, trends, and future outlooks for the lower Columbia from the Hugh Keenleyside Dam to the US border. The most recent are from 2005 and can be found on their website (www.criemp.org).

4.2.1 Data Analyses

Introduction

Snowmelt dominated regions around the world are expected to undergo seasonal shifts in streamflow under global climate change scenarios. Because these watersheds generally do not have long-term water storage capacities, these regions are expected to experience regional and seasonal water shortages (Barnett et al. 2005; Viviroli et al. 2011; Barnett et al. 2008). The Canadian portion of the Columbia Basin comprises only 15% of the total area; however, since it includes most of the high elevation area, this region provides 30-40% of the total annual runoff (Hamlet and Lettenmaier 1999b; Cohen et al. 2000) (Figure 4.2.1). The Columbia Basin supports over 400 dams producing a large portion of the energy needs of the Pacific Northwest, several unique ecosystems, numerous fish species, agriculture, and a growing population. The timing of volume and discharge, and their sensitivity to climate change, is therefore of widespread significance for both ecologic and economic reasons.

Headwater streamflow in the Columbia Basin is influenced by snow and glacial melt, this regime allows winter precipitation to be temporarily stored and later available to contribute to spring and summer runoff. These characteristics are highly sensitive to changes in regional temperature. Warmer temperatures mean less precipitation falls as snow, summer evapotranspiration increases, and glacier contributions decrease. These changes can translate into earlier peak flows and reduced summer flows (Cohen et al. 2000; Barnett et al. 2005; Hamlet and Lettenmaier 1999b; Schnorbus et al. 2012; Stahl and Moore 2006; Bolch et al. 2010). In the Columbia Basin of Canada, temperatures in the last century have risen by 1.2-2°C (Section 3). A shift toward an earlier freshet and center volume of flow (the date at which half the annual volume has been discharged) has been observed in streams across western North America (Stewart et al. 2005; Regonda et al. 2005); however, the results within the Canadian Columbia basin were not regionally consistent and trends non-significant. This is likely due to the strong geographic and climatic gradients across the region.

The Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) climate modes have well documented effects on temperature and precipitation, and consequently streamflow in the Pacific Northwest (Whitfield et al. 2010; Stewart et al. 2005; Gobena et al. 2013; Moore et al. 2009; Cayan et al. 1999). The PDO index is based on oscillations in sea surface temperatures in the North Pacific with specific phases that last 20-30 years (Mantua et al. 1997). The Cool negative phase of the PDO is associated with wetter and cooler winters in the Pacific Northwest, and the warm positive phase with warmer and drier winters. In the last century PDO cool phases occurred from 1947/48-1977/78, and most recently, a shift to a cool phase PDO is believed to have occurred in 1998 (citation). ENSO is based on oscillations in equatorial sea-surface temperatures that shift phases every 2-7 years (NOAA 2013c). Because ENSO affects the location of the jet stream, winter weather conditions in the Pacific Northwest are affected. During warm (El Niño/positive) phases, the jet stream is diverted south, leaving the Pacific Northwest warmer and drier. During cool (La Niña/negative) phase, the jet stream flows directly toward the Pacific Northwest bringing cooler, wetter winters. Persistent El Niño phases existed

through 1980s and 1990s; in the last decade more frequent La Niña events have occurred. At present, it is unclear to what extent anthropogenic climate change will influence the expression of climate modes in the Columbia Basin; it is likely given that warming will change the intensity, frequency of modal direction (negative/positive), and perhaps the oceanic loci of these ocean-atmosphere relationships.

The effects of both climate mode variability and anthropogenic climate warming have been examined on snowpack and streamflow characteristics in the Western USA (Pederson et al. 2013; Barnett et al. 2008; Abatzoglou 2011), with 35-60% of the variability ascribed to anthropogenic climate change (Barnett et al. 2008), particularly since 1980 (Pederson et al., 2013). However, this work has not been carried out explicitly for streams in the Canadian portion of the Columbia Basin. Here we evaluate the effects of a changing climate alongside natural climate mode fluctuations on historical stream hydrometrics across the diverse landscape of the Columbia Basin of Canada. Specifically, we seek to,

1) Determine the apparent relationships between climate variables on hydrologic variability both spatially and temporally across the Canadian portion of the Columbia Basin

2) Evaluate to what extent climate warming may already be influencing stream flow and,

3) Compare these results to current mechanistic model projections.

The research questions are addressed using historical records of stream flow, precipitation, temperature, Pacific Ocean climate modes, and downscaled global climate model simulations for British Columbia.

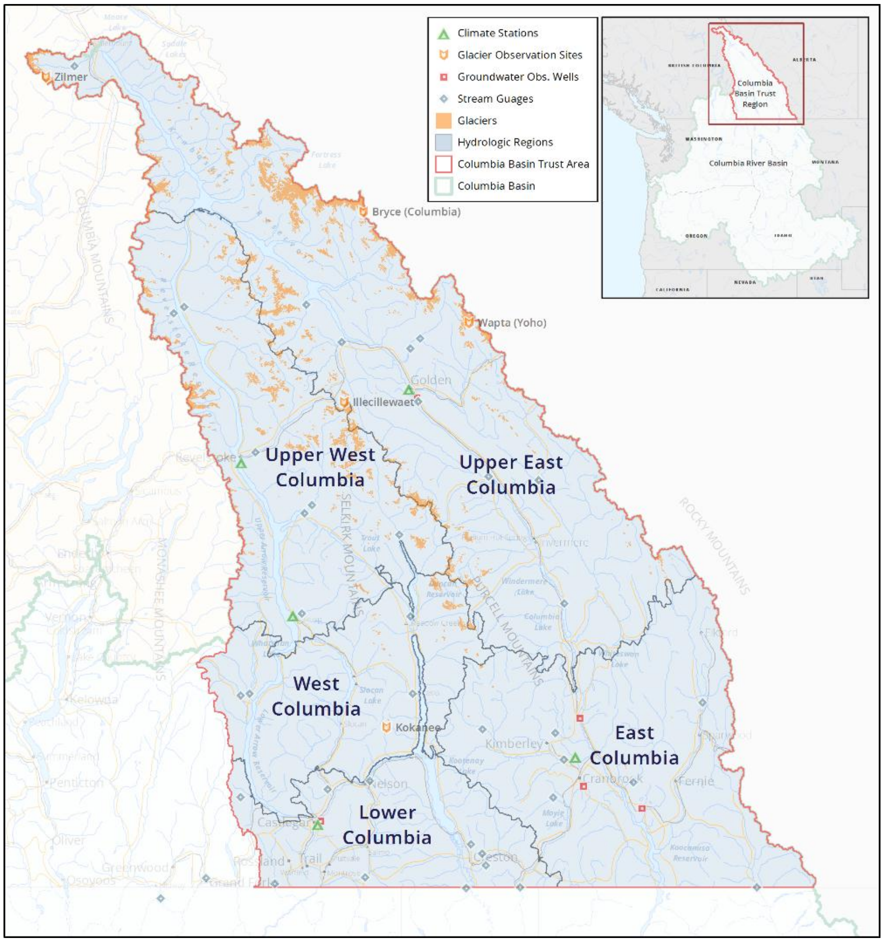


Figure 4.2.1. The geographic boundaries of the statistical regions in the Canadian Columbia Basin Trust Regions.

Methods

Data generation

Daily stream discharge data were obtained from Environment Canada for 36 streams in the Columbia Basin Trust Region (Figure 4.2.1). Years available varied by stream, though several records span >80 years (Table 4.2.1). For each stream we analyzed the following 12 flow metrics, total annual discharge normalized to catchment area (yield), annual minimum discharge, minimum late summer discharge and total late summer discharge (July 15 to September 15), and the annual peak (10 day average) and maximum discharge. We also analyzed trends in the following metrics on the timing of flow, the date of the annual minimum, maximum, and peak flows, the date of the onset of freshet, the date at which half the annual volume of discharge has been reached (center volume), and the onset of baseflow conditions. The onset of freshet/baseflow conditions were defined as the movement above/below a 45 degree angle on the annual cumulative discharge curve. The annual peak and the date of the annual peak flow are determined by average discharge over 10 days to avoid capturing a precipitation spike rather than the true annual maximum. Statistics are determined for the calendar year except for the annual minimum, and the date of the annual minimum, where statistics are determined

for the water year. The reason for this is that the annual minimum typically occurs through the winter months (December-February).

In addition to individual stream analysis, streams were statistically grouped into 4 regions using k-means cluster analysis on annual discharge values. These are Upper Columbia, Lower Columbia, Western Columbia and Eastern Columbia (Table 4.2.1, Figure 4.2.1). Upper Columbia was further divided into two groups due to stronger predictive power by using climate data from either side of the Selkirk Mountains (see below), Revelstoke climate data for streams in the Upper Western region, and Golden climate data for streams in the Upper East region (Figure 4.2.1).

We compiled composite trends for each region by using the regional average of the area-weighted daily stream yield. For this analysis we excluded incomplete years of data, streams with less than 40 years of data, and streams that are regulated above the monitoring station. The purpose of the composite trends is to provide a regional representative flow based on yield that can be applied to unmonitored streams within each region. The regions statistically divided into geographic regions that are generally representative of the wide range of altitude, geography, and climates found across the Canadian portion of the Columba Basin. However, northern streams with relatively higher proportions of abundant permanent ice and snow are underrepresented due to a lack of gauged streams in these types of catchments.

We validate the use the regional composite flow in the following manner. The yield in each of the five sub-basins is scaled up to the area that it covers within the Canadian portion of the Columbia Basin and then all five regions are summed to create an annual discharge curve for the last ~75 years. We then correlated this regional sum to actual flow of the Columbia at Birchbank. If the regional composites are representative, then a high statistical correlation is expected.

Because Pacific Climate Indices (e.g. PDO, ENSO), appear to influence the discharge, we evaluated the hydrographs for different periods, including the Cool Phase PDO (1947-1977,1998-2011), and the warm phase PDO (1977-1997), as well as the differences between cool/war ENSO (La Niña/El Niño), and positive and negative phases of the NOI.

Table 4.2.1 Stream meta-data for the Canadian Columbia Basin grouped by statistical region

Region	River Name	Years in Record	Env. Can. Identifier	Years of Data	Altitude	Latitude Decimal	Longitude Decimal	Drainage Area km^2	Nearest Climate Station to drainage area	% Glacier Cover
Upper East Columbia	Blaeberry	1966-2011	08NB012	42	987	51.4814	-116.9683	587	Golden	7.46
	Kicking Horse	1974-2011	08NA006	50	806	51.3000	-116.9778	1850	Golden	4.28
	Spillimacheen	1917-2011	08NA011	66	920	50.9042	-116.4058	1460	Golden	4.4
	Split	1974-2011	08NB016	38	1053	51.5269	-116.8986	81	Golden	0.29
	Columbia at Nicholson	1917-2011	08NA002	108	786	51.2436	-116.9131	6660	Golden	2.52
	Columbia at Fairmont	1946-1996	08NA045	53	831	50.3236	-115.8625	891	Golden	0.08
	Kootenay at Kootenay Crossing	1946-2011	08NF001	71	1298	50.8869	-116.0461	416	Golden	0
	Gold	1973-2011	08NB014	39	1220	51.6769	-117.7167	429	Golden	13.39
	Canoe	1971-2011	08NC004	37	1250	52.7314	-119.3844	305	Golden	19.08
	Beaver	1985-2011	08NB019	27	844	51.5097	-117.4617	1150	Revelstoke	7.86
Upper West Columbia	Beaton	1953-2010	08NE008	58	589	50.7358	-117.7289	97	Revelstoke	0
	Kirby	1973-2005	08ND019	33	775	51.6394	-118.6706	112	Revelstoke	2.96
	Goldstream	1964-2011	08ND012	53	660	51.6683	-118.5969	934	Revelstoke	6.08
	Illecillewaet	1964-2012	08ND013	49		51.0136	-118.0825	1150	Revelstoke	6.15
	Kuskanax	1964-2010	08NE006	50	823	50.2775	-117.7481	330	Revelstoke	0
	Incomappleux	1953-1995	08NE001	47	732	50.7736	-117.6767	1020	Revelstoke	10.56
	Duncan B	1964-2011	08NH119	50	690	50.6381	-117.0472	1310	Revelstoke	7.77
East Columbia	Bull	1919-2011	08NG002	93	863	49.4931	-115.3639	1520	Cranbrook	0.08
	Elk at natal	1953-2011	08NK016	62	1210	49.8661	-114.8683	1840	Cranbrook	0.73
	Mather	1973-2010	08NG076	40	1205	49.7250	-115.9250	135	Cranbrook	0
	Moyie A	1930-2011	08NH006	85	847	48.9994	-116.1786	1480	Cranbrook	0
	Moyie B	1965-2011.	08NH120	48	1178	49.4222	-115.9411	239	Cranbrook	0
	Flathead	1952-2011	08NP001	75	1526	49.0006	-114.4764	1110	Cranbrook	0
	St-Mary	1947-1994	08NG012	54	953	49.6003	-115.8628	2360	Cranbrook	0.03
		1973-2011	08NG077	39	1177	49.7417	-116.4500	208	Cranbrook	0
West Columbia	Barnes	1951-2011	08NE077	62	639	49.9075	-118.1253	204	Nakusp	0
	Inonoaklin	1972-2010	08NE110	36	531	49.8978	-118.1900	298	Nakusp	0
	Slocan	1914-2011	08NJ013	89	492	49.4606	-117.5644	3330	Castlegar	0.07
	Kaslo	1965-2011	08NH005	55	768	49.9075	-116.9519	442	Castlegar	0.56
	Lardeau	1946-2011	08NH007	65	566	50.2631	-116.9672	1640	Nakusp	1.01
Lower Columbia	Duck	1946-2011	08NH016	47	871	49.2028	-116.5322	57	Castlegar	0
	Sullivan	1965-2011	08NH115	50	1073	49.1039	-116.4264	6	Castlegar	0
	Big Sheep	1950-2011	08NE039	65	788	49.0167	-117.9444	347	Castlegar	0
	Granby	1967-2011	08NN002	54	595	49.0442	-118.4386	2060	Castlegar	0
	Kettle at Ferry	1929-2011	08NN013	84	849	48.9481	-118.7653	5700	Castlegar	0
	Arrow	1947-2011	08NH084	56	842	49.1589	-116.4511	78	Castlegar	0
	Boundary	1931-2011	08NH032	83	642	48.9972	-116.5681	242	Castlegar	0
	Salmo	1950-2011	08NE074	63	685	49.0469	-117.2936	1240	Castlegar	0
	Anderson	1967-2011	08NJ130	52	770	49.5014	-117.2597	9.1	Castlegar	0
	Deer	1959-2011	08NE087	54	1126	49.4250	-118.1900	82	Castlegar	0

Time series analysis

We evaluate trends in all hydrometric variables for the annual and monthly record from 1980 to 2011. We choose 1980 for several reasons: 1) it provides a standard time frame for comparison between streams, 2) it provides a method of comparison to other studies that have observed shifts since ~1980 (e.g. Pederson et al. 2013) and 3) because annual flow is strongly tied to oscillations in the PDO, we can potentially unintentionally bias our results towards negative trends by selecting a date that would reflect the switch from a cool to warm phase PDO that occurred in 1977/78, where a notable decrease in annual discharge occurred. Trend significance is calculated using the Mann-Kendall Statistic. We also use the Regime Shift Indicator (RSI) test developed by Rodionov, S.N., (2004). This test allows us to determine statistical breakpoints in the datasets where a regime shift has occurred (i.e. a shift in the average value of the parameter in question.) The RSI test is based on sequential analysis, where each new observation is used to test the null hypothesis, Ho: the existence of a regime shift. The test statistic

is a two-tailed Student's T-test. This RSI test allows for the detection of regime shifts at a variety of time scales (decadal, multi-decadal, centennial, etc.), without any a priori knowledge of the timing of a particular regime shift (Rodionov 2004). We used the RSI test to evaluate changes in hydrometric variables including annual yield, peak yield, and the late summer minimum and total yield.

The relationship between climate factors and stream hydrometrics

We used Pearson correlation coefficients to evaluate the statistical relationships between climate indices and regional stream hydrometrics. Since there is no single climate index that would completely describe the variability in moisture delivery and hence stream flow to the Columbia Basin, in addition to the established relationships with the PDO and ENSO, we examined the statistical relationships between regional climate data (rain, snow, total precipitation,) as well as annual and monthly stream hydrometrics against the following Pacific Ocean Climate indices; East Pacific/North Pacific Oscillation, the Western Pacific Index, Western Hemisphere Warm Pool, Aleutian Low, North Pacific Pattern, and the Northern Oscillation Index. The effects of Climate Indices on distal regions can lag by several months (citations). To evaluate the optimal lag time, we compared correlation analysis with monthly lag time for 1 month to 12 months for the climate and hydrometric variables listed above. Historical data for all climate Indices were downloaded from the National Oceanic and Atmospheric Administration (NOAA) online Climate and Weather Data resource (NOAA 2013a). All climate indices are available from 1900-2011. In additional we evaluated the relationships between stream hydrometrics and three temperature metrics: annual temperature, mean spring temperature (March to May), and the number of degree days over 18^0C. The latter is a measure of temperature intensity.

Results

The regional composite annual yield scaled to the full area of the Columbia Basin above Birchbank was consistent with measured flow at Birchbank and the two time series were correlated with an r^2 of 0.89, p<0.0001 (Figure 4.2.2). The strong correlation indicates that the regional composite yields are representative and can be used to evaluate the cause of regional change in flow.

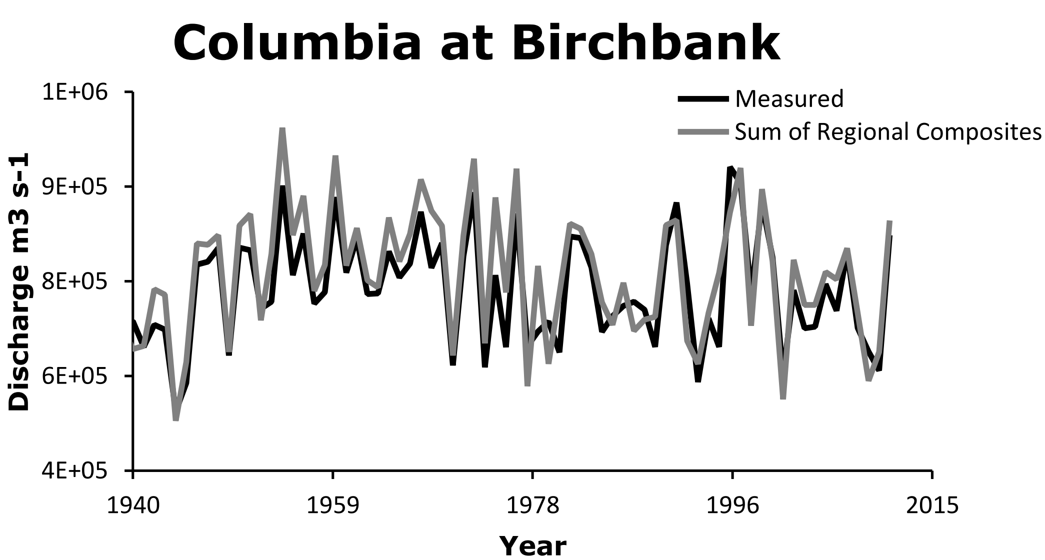


Figure 4.2.2. The measured discharge at Columbia at Birchbank (black line) compared to the sum of the 5 regional composites scaled up to their respective areas (grey line). The two time series correlate with an r^2 =0.86, p<0.0001.

Regional correlations to Pacific Climate Indices

Similar to other studies, we found that the PDO, ENSO, explained a significant portion of the variation in stream hydrometrics across the Columbia Basin (Table 4.2.2). Regression analysis indicated that the Northern Oscillation Index (NOI) also significantly explains moisture delivery to the Columbia Basin. This is likely because the NOI may be effective at representing inter-annual to decadal variability at extra-tropical latitudes because it reflects changes in the Northeast Pacific and therefore has a physical connection to climate in the Columbia (Schwing et al. 2002). The NOI is similar to the Southern Oscillation Index as a northern counterpart, but is larger in amplitude and highlights events not captured by the SOI. We found a 6-month lag in the annual averages of the climate indices explained the highest amount of variation, the historical variation of all three climate indices are shown in Appendix 1 (Figures A1-A3).

We found strong regional differences in the correlation coefficients for the PDO, ENSO, and NOI that roughly conform to the five statistical hydrometric regions. Table 4.2.2 provides correlation coefficients for regional composite time series against the Pacific climate indices and Figures 4.2.3 through 4.2.5 show the regional variability in coefficients for the individual streams. Canoe Creek in the upper reaches of the CBTR stands out as being the only stream to have a positive correlation to the PDO and ENSO. The East Columbia region showed the strongest statistical relationships and the Lower Columbia region showed the weakest relationships to all Pacific climate indices.

We evaluated differences between the mean annual yield in the positive and negative phases of the PDO, ENSO and NOI. We found the differences to be stronger for the NOI and PDO with mean differences of 11% and 9% (Table 4.2.3). We found strong interactions between the PDO and the NOI where the lowest discharge years were related to the combination of positive PDO and negative NOI, and the highest discharge years to the combination of negative PDO and positive NOI, regardless of the ENSO phase (Figures 4.2.6-4.2.10). The combination of positive PDO and negative NOI tended towards an earlier onset of freshet and an earlier center volume. The combination of a positive NOI and a negative PDO phase had on average a 14% greater yield than visa- versa.

Table 4.2.2 Correlation coefficients of regional stream hydrometrics to Pacific Climate Indices. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

		Annual Yield	Winter Min	Low flow Volume	Late Summer Min	Late Summer Volume	Onset freshet	Center volume	Date of Peak flow	Date of summer Min	Peak Flow	Maximum Flow
Upper East Columbia	PDO	-0.34***	-0.04	-0.02	-0.21**	-0.33***	-0.26**	-0.03	-0.11	-0.22**	-0.41***	-0.39***
	ENSO	-0.32***	0	0	-0.38***	-0.37***	-0.25**	-0.18*	-0.21**	-0.14	-0.40***	-0.35***
	NOI	0.24**	-0.01	0.18	0.45***	0.42***	0.25**	0.32***	0.30***	-0.01	0.32***	0.32***
Upper West Columbia	PDO	-0.32**	-0.11	-0.02	-0.27**	-0.36***	-0.26**	-0.29**	-0.29**	-0.19	-0.30**	-0.19
	ENSO	-0.32**	0	-0.02	-0.40***	-0.41***	-0.16	-0.32**	-0.26**	-0.09	-0.36**	-0.28**
	NOI	0.27**	0	-0.02	0.42***	0.41***	0.06	0.42***	0.48***	-0.03	0.24*	0.27**
East Columbia	PDO	-0.37***	-0.12	-0.16	-0.25**	-0.23**	-0.26**	-0.15	-0.12	-0.04	-0.45***	-0.42***
	ENSO	-0.38***	-0.20*	-0.24**	-0.24**	-0.22**	-0.32**	-0.13	-0.13	0.04	-0.40***	-0.34***
	NOI	0.22**	-0.04	0.05	0.14	0.10	0.26**	0.19	0.14	-0.06	0.21**	0.23**
West Columbia	PDO	-0.25**	0.08	0.03	-0.31***	-0.37***	-0.29**	-0.24**	-0.23**	-0.04	-0.25**	-0.20*
	ENSO	-0.32***	-0.07	-0.06	-0.33***	-0.40***	-0.18	-0.32***	-0.39***	0.08	-0.29**	-0.29**
	NOI	0.20*	-0.17	-0.09	0.29**	0.36***	0.20*	0.38***	0.36***	-0.01	0.17	0.21*
Lower Columbia	PDO	-0.27**	-0.10	-0.05	-0.15	-0.13	-0.22**	-0.22**	-0.27**	0.15	-0.34***	-0.29**
	ENSO	-0.24**	-0.15	-0.09	-0.11	-0.15	-0.36***	-0.31**	-0.34***	0.22**	-0.28**	-0.25**
	NOI	0.09	-0.05	-0.02	0.08	0.09	0.26**	0.31**	0.32***	-0.13	0.09	0.11

Table 4.2.3 Cumulative annual yield ($m^3 s^{-1} km^{-2}$) for the composite time series for the five statistical hydrograph regions. Yield during a negative PDO is 6.1% greater than during a positive PDO, Yield during a negative ENSO is 8.7% greater than during a positive ENSO, and yield during a positive NOI is 10.9% greater than during a positive NOI.

	Pos. PDO	Neg. PDI	Difference (%)	Pos. ENSO	Neg. ENSO	Difference (%)	Pos. NOI	Neg. NOI	Difference (%)
Upper East Composite	8.3	8.8	8.6	8.2	8.9	5.4	8.8	8.2	6.9
Upper West Composite	17.1	17.8	3.8	16.7	17.9	6.7	17.8	16.7	6.9
East Composite	4.3	4.7	8.9	4.2	4.8	12.9	4.7	4.2	11.9
West Composite	9.9	10.4	4.5	9.7	10.6	8.6	10.5	9.5	11.3
Lower Composite	5.8	6.0	4.8	5.6	6.2	9.8	6.1	5.5	10.5
Average			6.1			8.7			10.9

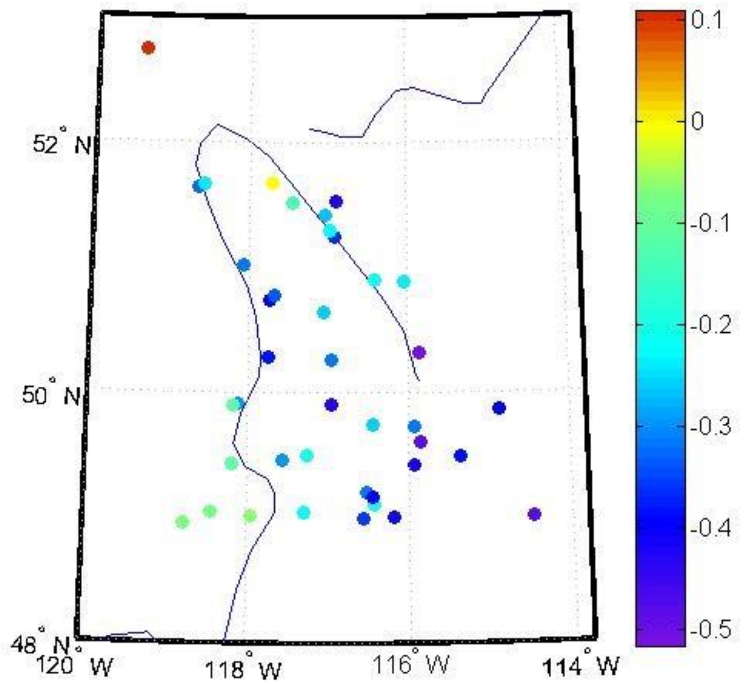


Figure 4.2.3 Map of Pearson correlation coefficients of the PDO to annual yield

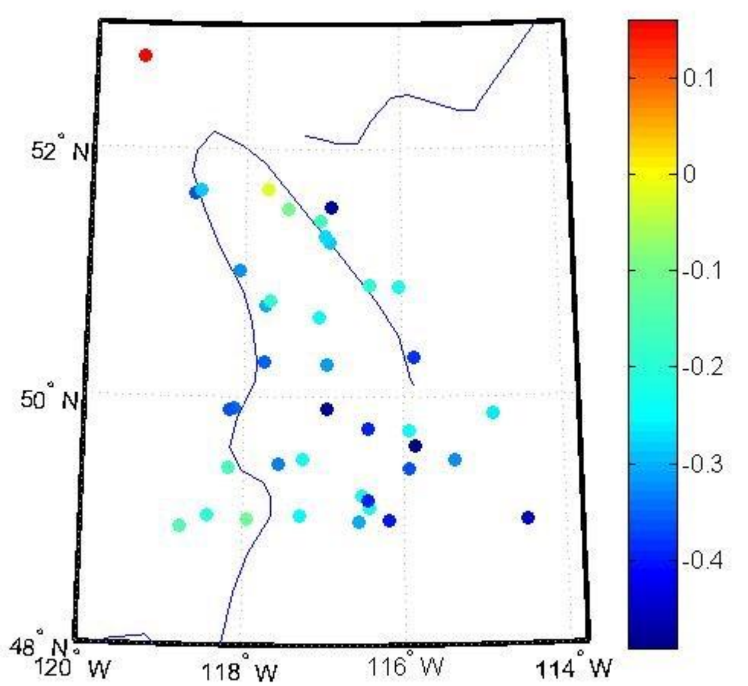


Figure 4.2.4 Map of Pearson Correlation coefficients of the ENSO to annual yield

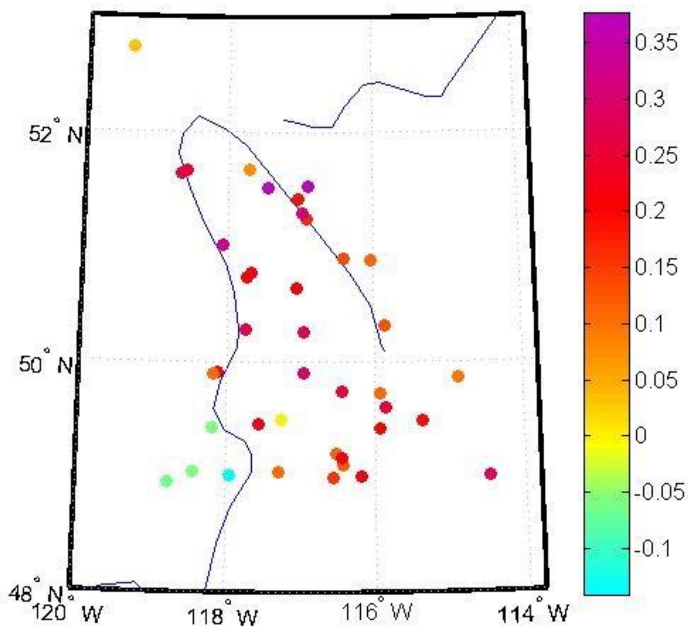


Figure 4.2.5 Map of Pearson Correlation coefficients of the NOI to annual yield

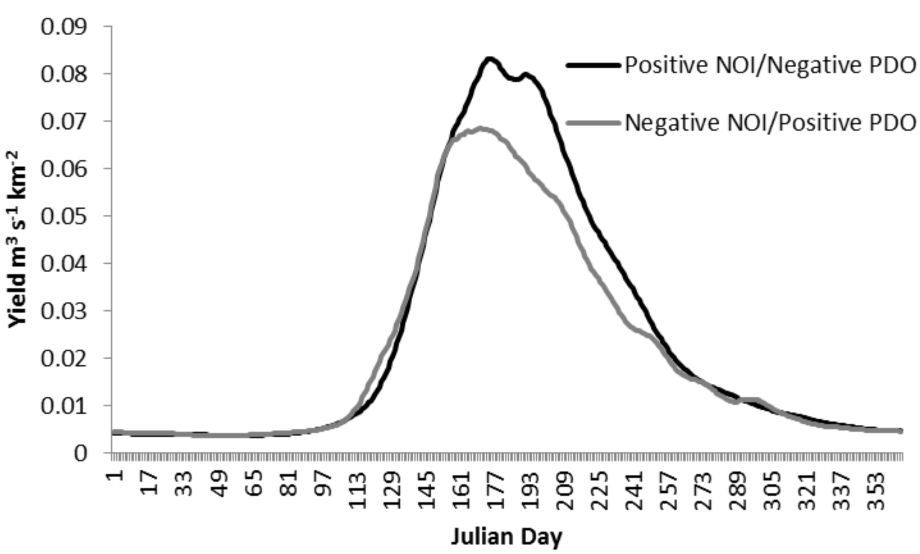


Figure 4.2.6 Average hydrograph for the Upper East Columbia statistical region for the years of Negative PDO/Positive NOI (black) and Positive PDO/Negative NOI (grey).

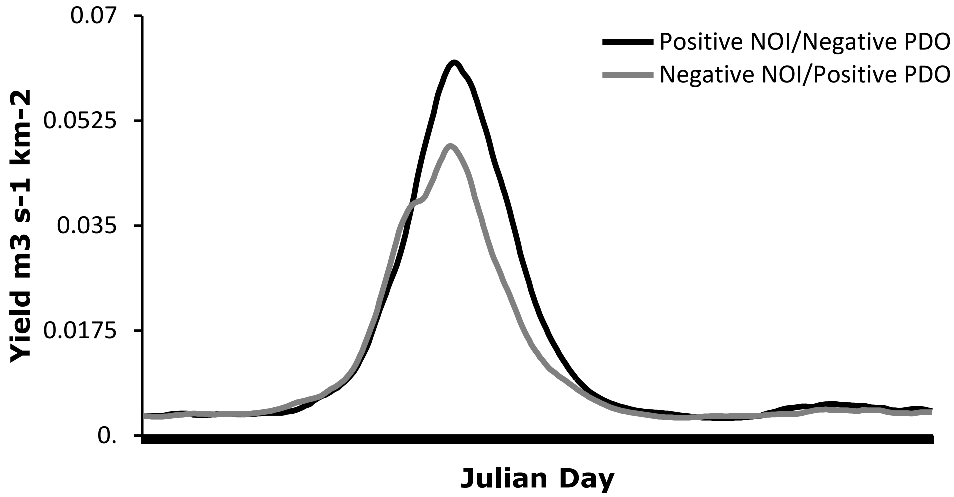


Figure 4.2.7 Average hydrograph for the Upper West Columbia statistical region for the years of Negative PDO/Positive NOI (black) and Positive PDO/Negative NOI (grey).

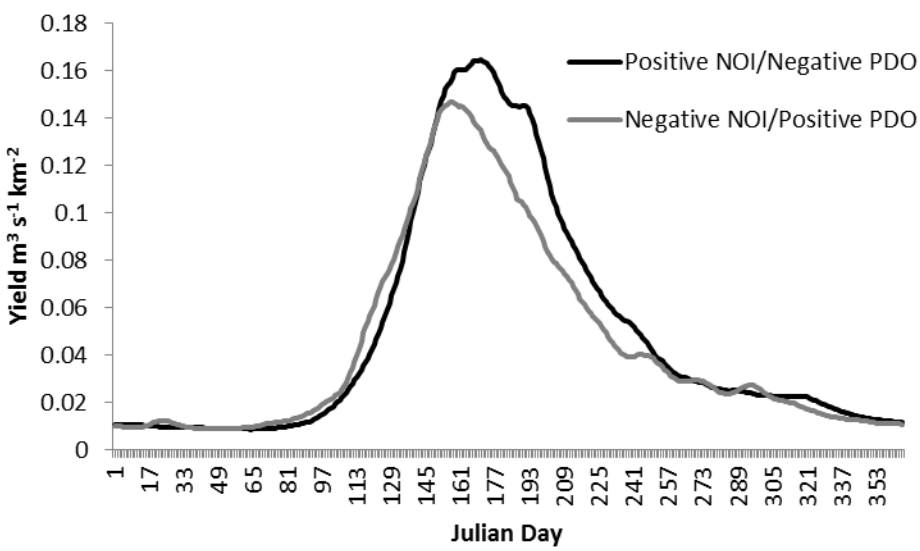


Figure 4.2.8 Average hydrograph for the East Columbia statistical region for the years of Negative PDO/Positive NOI (black) and Positive PDO/Negative NOI (grey).

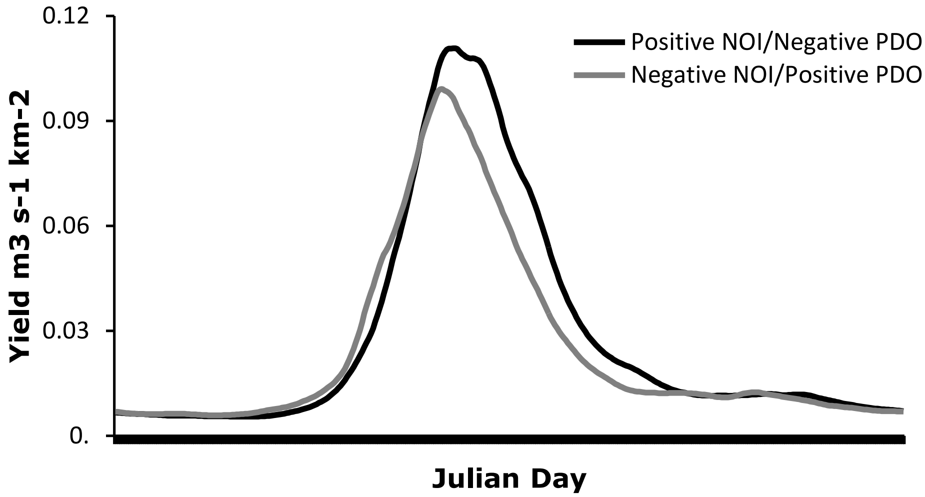


Figure 4.2.9 Average hydrograph for the West Columbia statistical region for the years of Negative PDO/Positive NOI (black) and Positive PDO/Negative NOI (grey).

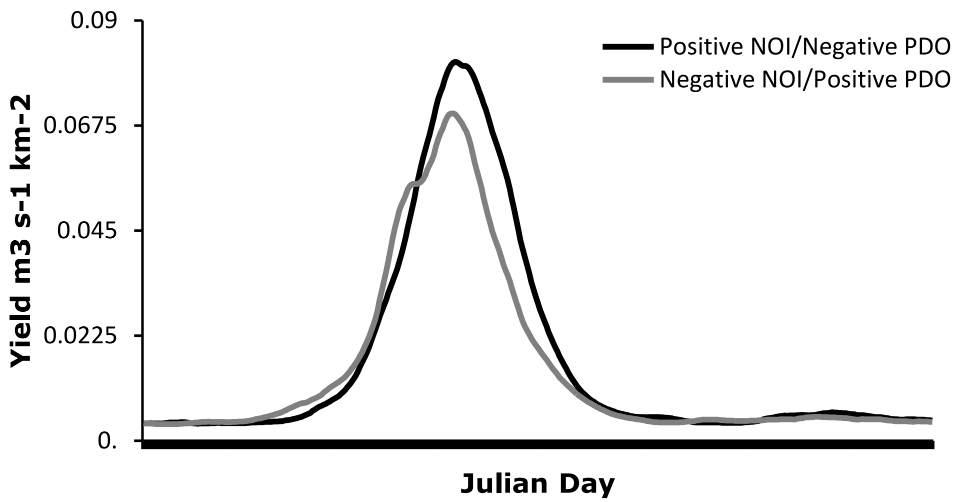


Figure 4.2.10 Average hydrograph for the Lower Columbia statistical region for the years of Negative PDO/Positive NOI (black) and Positive PDO/Negative NOI (grey).

Since 1980, the annual yield has decreased in >85% of streams, and the late summer minimum and discharge have decreased in 95 and 98% of streams analyzed (Table 4.2.4, Figure 4.2.11,4.2.12). Composite time series show regional differences, with greater declines in summer flow in the lower and East Columbia regions (Table 4.2.4). The West and Lower Columbia regions exhibit the strongest decline in annual yield, the former significant at p<0.1. Peak flows have decreased in most regions, though non-significantly (Figure 4.2.13). Changes in the center volume are inconsistent between regions though there is a tendency for the onset of freshet to have moved to later in the year.

Table 4.2.4. Pearson correlation coefficients from 1980 to 2011 with percent change for flow metrics or days for timing metrics in brackets. Stars indicate significance with * *p*<0.01*p*<0.0.5, *** *p*<0.001.**

	Annual Yield (%)	Winter Min (%)	Low flow Volume (%)	Late Summer Min (%)	Late Summer Volume (%)	Peak flow (%)	Onset freshet (days)	Center Volume (days)
Upper East Columbia	-0.13 (-5)	-0.05 (-2)	-0.2 (-21)	-0.34 (-15)**	-0.22 (-9)	-0.1 (-5)	-0.01 (-2)	-0.07 (-1)
Upper West Columbia	-0.01 (0)	0.07 (5)	0.28 (27)	-0.27 (-14)	-0.19 (-12)	-0.16 (-6)	0.18 (6)	-0.06 (0)
East Columbia	-0.1 (-6)	-0.16 (-8)	-0.19 (-12)	-0.21 (-15)	-0.19 (-17)	-0.003 (-5)	0.19 (7)	0.18 (6)
West Columbia	-0.36 (-15)*	-0.15 (-4)	-0.19 (-7)	-0.48 (-35)**	-0.36 (-30)	-0.27 (-15)	0.11 (3)	-0.1 (-1)
Lower Columbia	-0.17 (-11)	-0.21 (-16)	-0.28 (-20)	-0.36 (-32)*	-0.31 (-31)	-0.06 (-10)	0.18 (7)	0.08 (4)

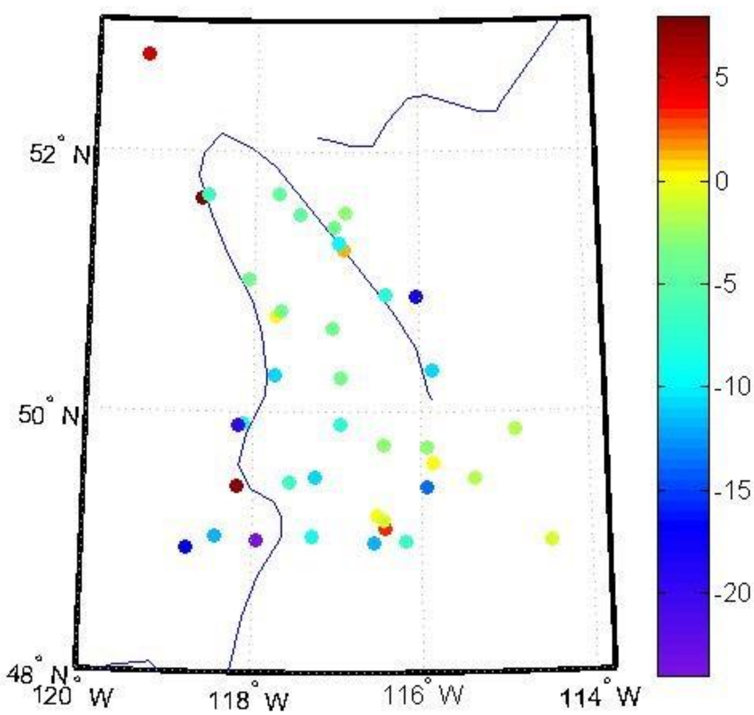


Figure 4.2.11 Percent change in the mean annual yield ($m^3 s^{-1} km^{-2}$) in all streams from 1980-2011.

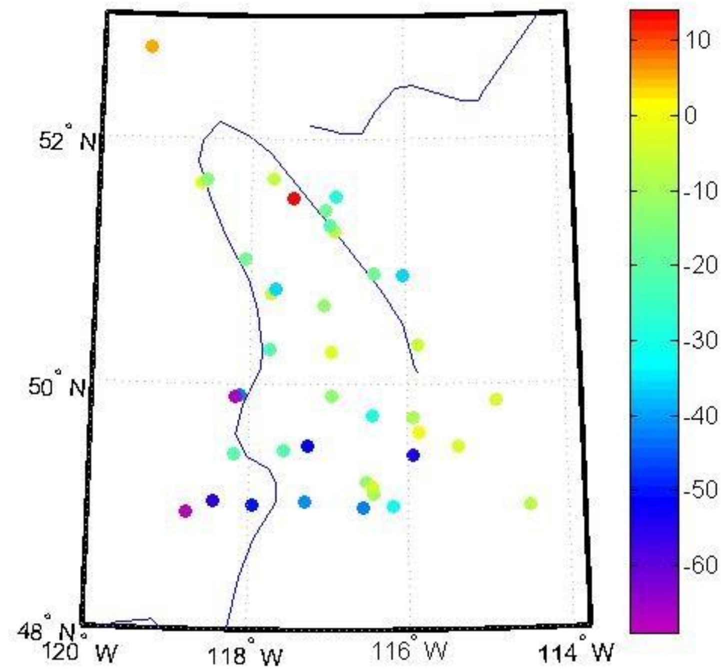


Figure 4.2.12 Percent change in the late summer minimum yield ($m^3\ s^{-1}\ km^{-2}$) from 1980-2011

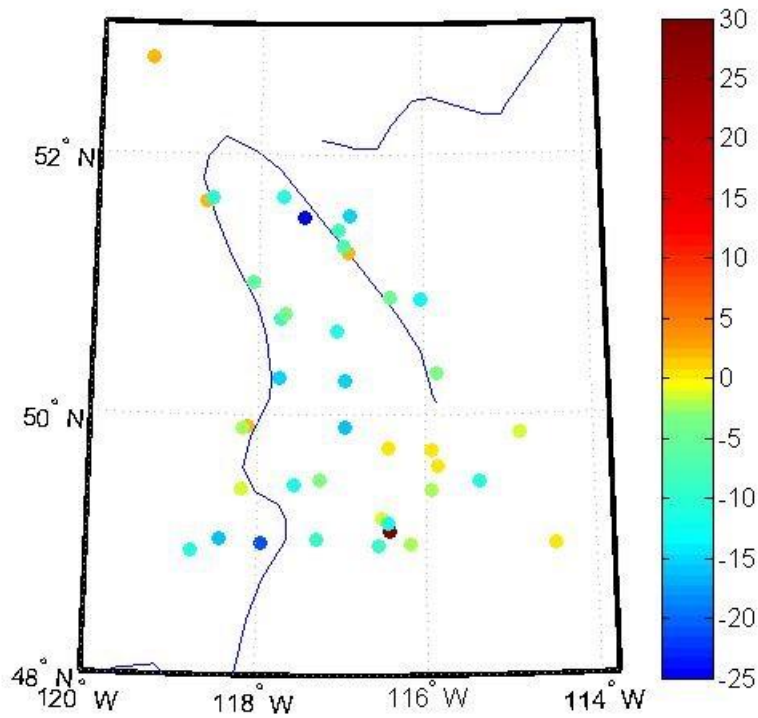


Figure 4.2.13 Percent change in peak yield ($m^3\ s^{-1}\ km^{-2}$) from 1980-2011

Regional changes in volume, timing of flow and hydrograph shape

Upper East Columbia

The Upper East Columbia has 9 monitored streams and rivers, including two stations along the Columbia River itself (Table 4.2.1, Figure 4.2.1). The Upper East Columbia region encompasses an area of 26,912 km^2. All but two monitored streams, Spillimacheen and Split creek, have greater than 2% glacial area within their catchments. Seven of the nine streams show non-significant reductions in annual yield with an average decline of -5% from 1980 to present (Table 4.2.5). Kirby and the Columbia at Nicholson show non-significant increases in annual flow through this time period. The late summer minimum has declined in all streams but Beaver and Canoe Creek, and significantly so in 5 streams (p<0.01) with an average decline of -13% (Table 4.2.5). Peak and maximum flows have decreased in 7 and 8 streams with an average decline of -9 and -15%. Winter flows have increased in most streams, and significantly so in 2 streams. When flow is partitioned monthly, a pronounced and often significant decrease in March, April, July and August flows from 1980 to 2011 is present (Table 4.2.6). Exceptions include Gold, and Beaver Creeks, which show non-significant increases in flow through August and September. Changes in the timing of flow vary from stream to stream with no real overall trend.

The regional composite time-series and hydrograph are in general good representations of the temporal changes occurring in most streams. A correlation matrix of annual yield indicates that most streams in the Upper East Columbia Region are strongly and significantly correlated (Table 4.2.7). An exception is Canoe Creek, where the correlation to the composite trend is weaker (r=0.44), but still significant (p<0.01). The RSI test on the Upper East Columbia Composite indicates a significant decline in annual yield, late summer yield, and peak yield, around mid-1970's (p<0.001,p0.0001,p<0.05), and non-significant declines in 2009 (Figures 4.2.14-4.2.16). The RSI test for the late summer minimum indicates significant declines in 1936 (p<0.0005), and 1992 (p<0.05).

We compiled the average hydrograph through the main shifts in the PDO, the cool phase from 1947 to 1977, the warm phase from 1978 to 1986, and the present cool phase from 1998 to 2011. We chose the PDO due to the strong correlations to yield (Table 4.2.4, Figure 4.2.3), and because major PDO phases last several decades. This allows us to evaluate changes in the hydrograph through these major phases. There has been a notable decline in maximum flow, late summer flows, and the total annual volume of flow (Figure 4.2.17-4.2.18). In comparing the cool PDO phase from 1947-1977, with the current Cool phase 1998-present PDO phase, we find that the present cool PDO phase has 4% lower annual yield (p<0.001), 18% lower late summer yield (p<0.001), and 15% lower maximum flow (p<0.05). We find non-significant declines in winter volume, and no significant changes in the timing of flow, including the onset of freshet, center volume, or the dates of maximum and minimum flows. The stations on the Columbia (Nicholson, Fairmont), Split, and Kootenay rivers underwent the largest changes in hydrograph shape through the PDO shifts. Again, Beaver creek is distinctly different showing no change between time periods, and Canoe Creek shows an increase in the post 1998 time period.

Table 4.2.5. Changes in flow for individual stream records in the Upper East Columbia from 1980-2011. Stars indicate Mann-Kendall trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Stream	Percent of Catchment Glaciated	Annual Yield %	Winter Min. Yield %	Low flow Yield Sum	Late Summer Min. Yield %	Late Summer Yield Sum%	Onset freshet (days)	Center volume (days)	Date of Max flow (days)	Date of summer Min (days)	Peak Yield	Maximum Yield
Blaeberry	7.46	-4	13	8	-16*	-13	2	-8	0	-11	-8	-13
Kicking Horse	4.28	-10	-12	-33	-20***	-17*	4	0	10	0	-7	-12
Gold	13.39	-5	27**	-41	-6	-15	-7	-1	-8	2	-11*	-23**
Beaver	7.86	-5	31	7	14	6	34	9**	10	4	-25**	-39**
Spillimacheen	4.4	-8	16	17	-18**	-16*	-5	0	9	1	-5	-22*
Split	0.29	-3	29**	28	-28**	-18	-5	-1	-2	0	-15	-18
Canoe	19.08	5	-24*	-4	6	-4	-4	-1	0	3	2	9
Columbia at Nicholson	2.52	1	-7	-20	-6	2	0	3	0	-1	2	2
Columbia at Fairmont	0.08	-11	29	-44**	-5	-12	-18	1	39	-3	-3	2
Kootenay at Kootenay Crossing	0	-18	-20	-8	-36**	-37*	3	-1	10	-3	-13	-13
Average		-7	9	-10	-13	-12	2	1	2	1	-9	-15
Upper East Composite		-5	-2	-21	-15**	-9	-2	-2	12	3	-5	-16

Table 4.2.6. Monthly correlation coefficients for individual streams flow in the Upper East Columbia from 1980-2011. Bold highlights significant Mann Kendall trends at *p*<0.10 or lower, shaded areas highlight negative trends.

Monthly	Uppe East Composite	Blaeberry	C. Nicholson	Kicking Horse	Spillimacheen	Split	Kootenay	C. Fairmont	Gold	Beaver	Canoe
January	0.12	-0.08	-0.05	0.17	-0.05	0.20	-0.06	0.06	0.20	0.25	**-0.37**
February	0.15	0.17	-0.15	0.12	0.15	**0.23**	-0.01	-0.03	**0.29**	0.12	**-0.43**
March	0.06	0.22	-0.14	0.17	0.09	**0.39**	0.01	0.14	**0.46**	0.13	**-0.49**
April	-0.19	-0.10	-0.07	-0.21	0.08	-0.03	-0.17	**0.60**	-0.08	**-0.35**	0.00
May	-0.16	**-0.26**	0.01	-0.20	-0.01	**-0.26**	-0.15	0.19	-0.11	-0.20	0.04
Jublaeday	0.06	0.07	0.05	0.05	0.02	0.17	0.08	0.11	0.15	-0.03	0.09
July	0.11	0.05	0.13	-0.03	-0.23	0.00	-0.17	0.10	0.11	0.08	0.16
August	-0.22	**-0.35**	-0.16	**-0.34**	**-0.59**	-0.22	**-0.30**	-0.04	-0.39	-0.06	-0.27
September	-0.11	-0.30	-0.04	-0.22	**-0.40**	-0.21	-0.09	-0.04	0.07	0.16	-0.01
October	0.23	0.25	0.26	0.24	0.14	0.24	0.03	-0.08	0.09	0.08	0.10
November	0.09	0.13	0.07	0.16	0.04	0.08	-0.02	0.09	0.09	-0.11	0.02
December	-0.06	-0.08	-0.15	0.04	**0.33**	-0.03	-0.06	0.33	0.13	-0.15	0.08

Table 4.2.7 Correlation matrix for streams and the regional composite time series for the Upper East Columbia Region.

	UE Comp.	Blae.	C. Nich.	C. Fair.	Kick H.	Spill.	Split	Beaver	Canoe	Koot.
Upper East Composite	1.00									
Blaeberry	0.92	1.00								
C. Nicholson	0.92	0.80	1.00							
C. Fairmont	0.89	0.83	0.92	1.00						
Kicking Horse	0.95	0.84	0.85	0.84	1.00					
Spillimacheen	0.92	0.80	0.88	0.84	0.86	1.00				
Split	0.88	0.78	0.70	0.72	0.83	0.75	1.00			
Beaver	0.74	0.66	0.74	0.53	0.70	0.85	0.43	1.00		
Canoe	0.44	0.62	0.47	0.46	0.41	0.50	0.29	0.50	1.00	
Kootenay	0.84	0.81	0.84	0.86	0.90	0.82	0.78	0.51	0.39	1.00

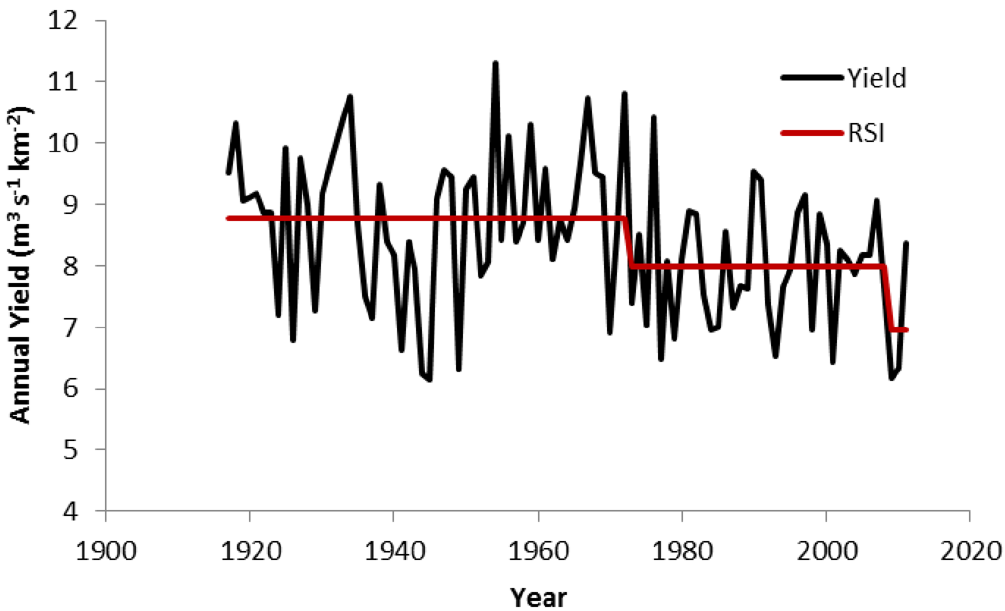


Figure 4.2.14 Regime Shift Indicator test for the Upper East Columbia composite annual yield showing a significant decline in 1973 *p*<0.001, and a non-significant decline in 2009 *p*=0.28

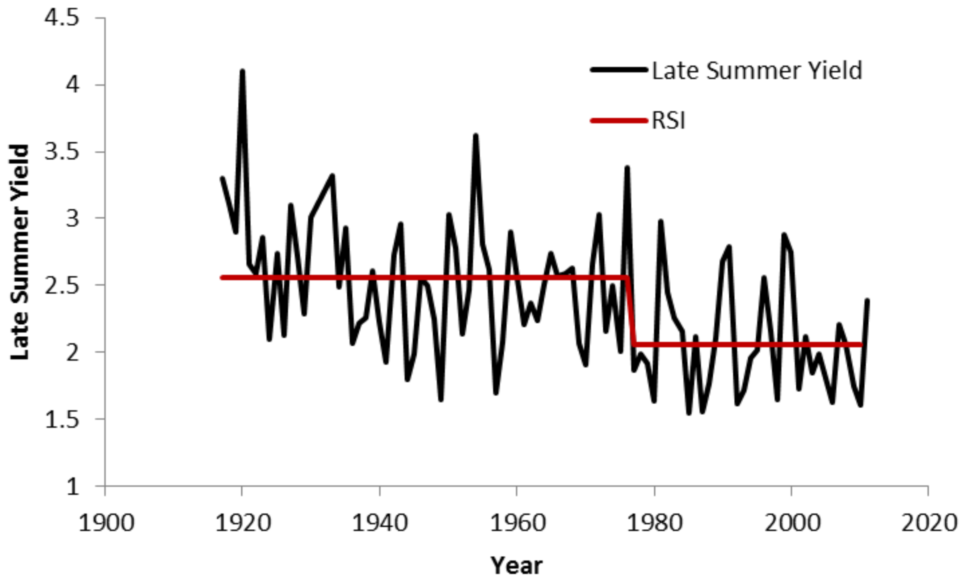


Figure 4.2.15 Regime Shift Indicator test for the Upper East Columbia composite late summer yield showing a significant decline in 1973 *p*<0.001.

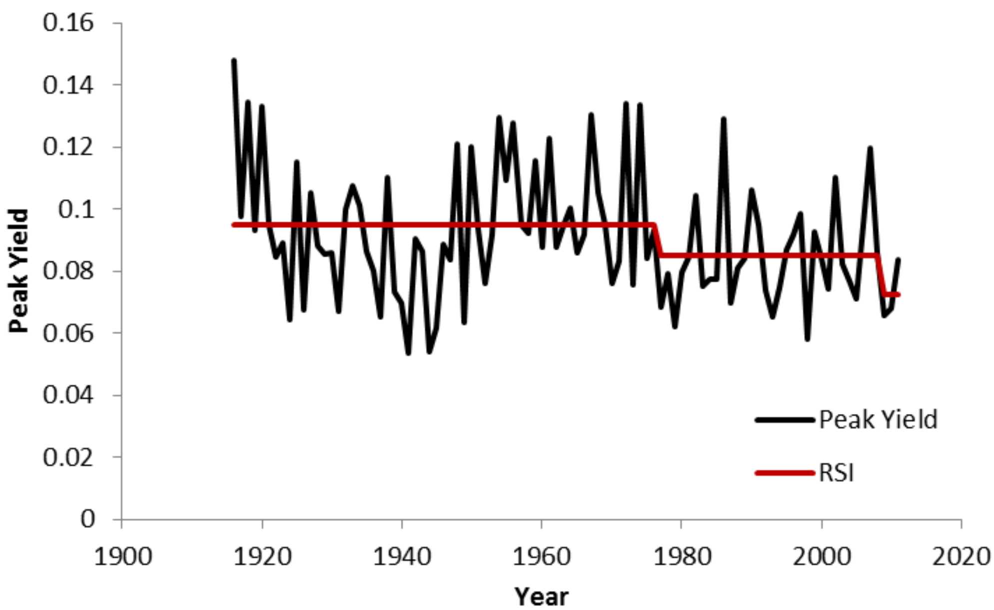


Figure 4.2.16 Regime Shift Indicator test for the Upper East Columbia composite peak yield showing a significant decline in 1977 (*p*<0.05), and a non-significant decline in 2009 (*p*=0.14).

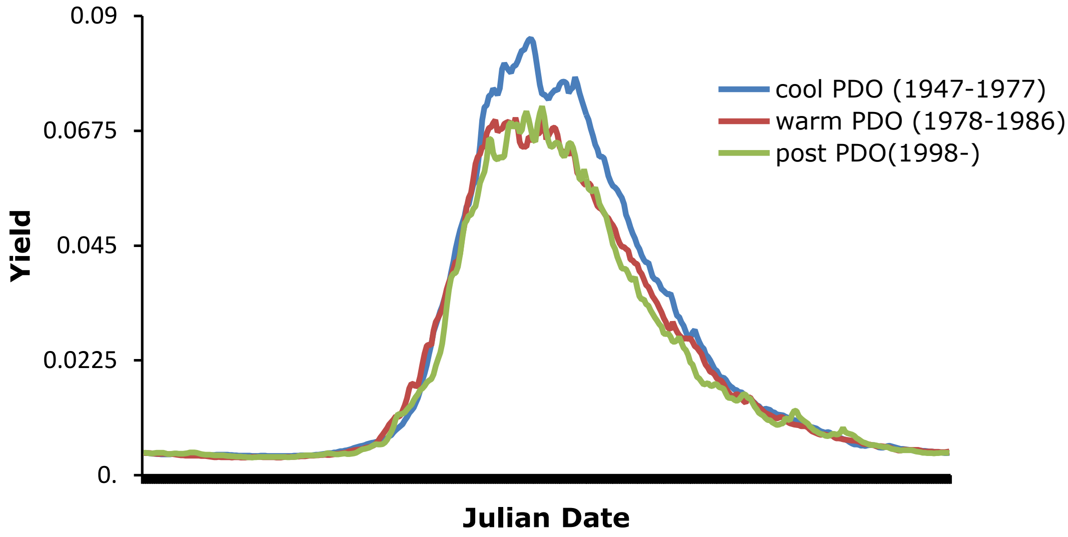


Figure 4.2.17 Hydrograph changes between the three main PDO phases in the last 65 years for the Upper East Columbia composite time series.

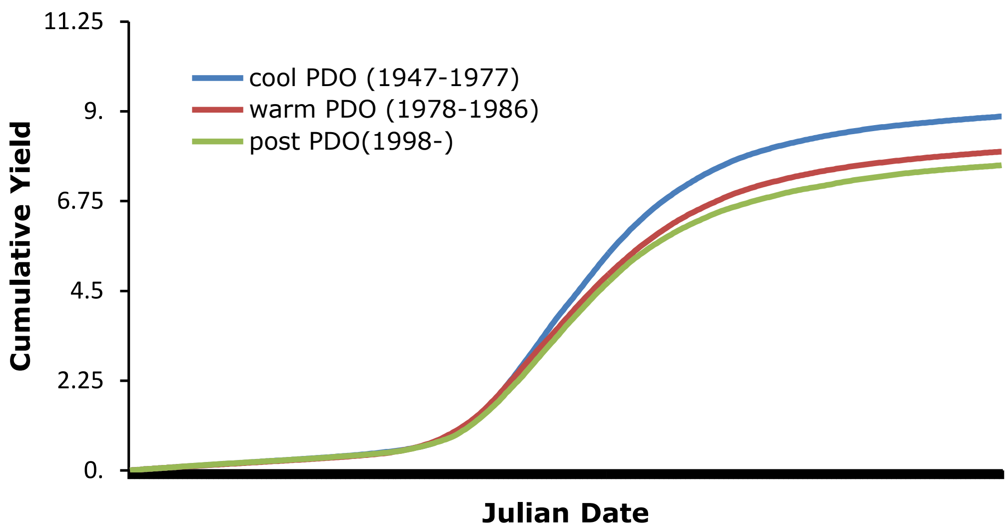


Figure 4.2.18 The cumulative yield for the three main PDO phases in the last 65 years for the Upper East Columbia composite time series.

Upper West Columbia

The Upper West Columbia has 7 monitored streams and rivers in an area of 15,487 km^2. Five of the streams have greater than 2% glacial area coverage in their catchments (Table 4.2.8). Five of the seven streams show non-significant declines through the 1980-2011 period. Anomalies include Beaton Creek, which shows no change in flow, and Kirby Creek, which shows a +8% increase. The late summer minimum and volume of flow shows pervasive and significant declines. The average decline in the late summer volume is -9%. Maximum and peak flows show strong declines averaging at -17% and -7%. There were no significant changes in the timing of flow for this region, but a there was a tendency for the onset of freshet to have moved to later in the year by 2-8 days and the date of maximum flow by 1 – 2 weeks. Similar to the Upper East Columbia, monthly significant declines primarily occur in August (Table 4.2.9).

The regional composite time series and hydrographs for the Upper West Columbia region appear to be good representations of what is occurring in most of the monitored streams. A correlation matrix of annual yield confirms that the composite trend is significantly and strongly correlated to other streams in the region (Table 4.2.10). The RSI test on indicates a significant decline in annual yield around 1984 (p<0.1) (Figure 4.2.19), a significant decline in the late summer yield in 2001 (p<0.05) (Figure 4.2.20), and a non-significant decline in the peak yield in 2009 (p=0.38) (Figure 4.2.21).

The regional composite hydrographs show declines in maximum and late summer flow with little to no change in the timing of flow between the major PDO periods (Figure 4.2.22). Hydrograph changes were not significant in the composite model. Declines in maximum and late summer flow were most notable in Beaton and Kuskanax streams, both of which have less than 2% glacier cover. Both streams show significant declines in the maximum flow by 21% and 33% (p<0.05). Both streams also showed an earlier onset of freshet, by 6-9 days at p<0.1 for Beaton, and p<0.01 for Kuskanax. The Illecillewaet and Duncan rivers were the least changed through the time periods, with no significant changes to the timing of flow.

Table 4.2.8 Changes in flow for individual stream records in the Upper West Columbia from 1980-2011. Stars indicate Mann-Kendall trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Stream	Percent of Catchment Glaciated	Annual Yield %	Winter Min. Yield %	Low flow Yield Sum	Late Summer Min. Yield %	Late Summer Yield Sum %	Onset freshet (days)	Center volume (days)	Date of Max flow (days)	Date of summer Min (days)	Peak Yield	Maximum Yield
Beaton	0	0	15	11	-6	-13	2	1	4	-1	-9*	-12
Kirby	2.96	8	11	-10	-2	7	1	-1	-1	0	2	-11
Goldstream	6.08	-7	-13	15	-14*	-16	1	0	11	-1	-10*	-14*
Illecillewaet	6.15	-4	-19*	16	-16	-13	8	0	12	0	-6	-5
Kuskanax	0	-11	3	9	-22	-34*	4	2	0	0	-15	-9
Incomappleux	10.56	-4	-15	8	-36**	-21	2	-11	24	7	-4	-45
Duncan B	7.77	-4	-2	14	-12	-11	2	3	8	-1	-11*	-25**
Average		-4	4	9	-12	-11	3	-1	8	1	-7	-17
Upper West Composite		0	5.3	27	-13.9	-12	6	0	10	-3	-6	-12*

Table 4.2.9. Monthly correlation coefficients for individual streams flow in the Upper West Columbia from 1980-2011. Bold highlights significant Mann Kendall trends at *p*<0.10, shaded areas highlight negative trends.

	Upper West Composite	Beaton	Kirby	Goldstream	Illecillewaet	Kuskanax	Incomappleux	Duncan B
January	0.16	0.29	0.19	0.04	0.10	-0.27	0.04	0.39
February	0.05	0.07	0.01	-0.09	0.10	-0.16	-0.04	0.19
March	0.03	0.00	0.13	-0.04	0.09	-0.09	-0.15	-0.15
April	-0.13	-0.04	-0.11	-0.16	-0.07	**0.46**	-0.09	0.03
May	-0.03	0.08	-0.13	-0.10	-0.12	0.26	-0.10	0.05
June	0.11	-0.03	-0.12	0.05	-0.16	0.07	0.01	0.01
July	-0.04	-0.11	-0.04	-0.04	-0.28	**-0.36**	-0.02	0.04
August	**-0.28**	-0.09	**-0.36**	**-0.28**	**-0.25**	-0.29	-0.33	0.10
September	-0.10	0.04	-0.25	-0.18	0.03	-0.24	-0.05	0.20
October	0.24	0.28	0.15	0.23	0.14	0.20	0.23	0.36
November	0.11	0.21	0.04	0.08	0.06	0.02	0.04	0.22
December	0.05	0.20	-0.07	-0.23	0.16	0.40	0.04	0.24

Table 4.2.10 Correlation matrix for streams and the regional composite time series for the Upper West Columbia Region.

	UW Comp.	*Beaton*	*Kirby*	*Golds.*	*Ille.*	*Kusk.*	*Inco.*	*Duncan*
Upper West Composite	1.00							
Beaton	0.97	1.00						
Kirby	0.87	0.84	1.00					
Goldstream	0.92	0.88	0.85	1.00				
Illecillewaet	0.95	0.90	0.83	0.93	1.00			
Kuskanax	0.91	0.84	0.82	0.85	0.85	1.00		
Incomappleux	0.91	0.80	0.73	0.83	0.92	0.85	1.00	
Duncan	0.92	0.88	0.77	0.89	0.89	0.85	0.92	1.00

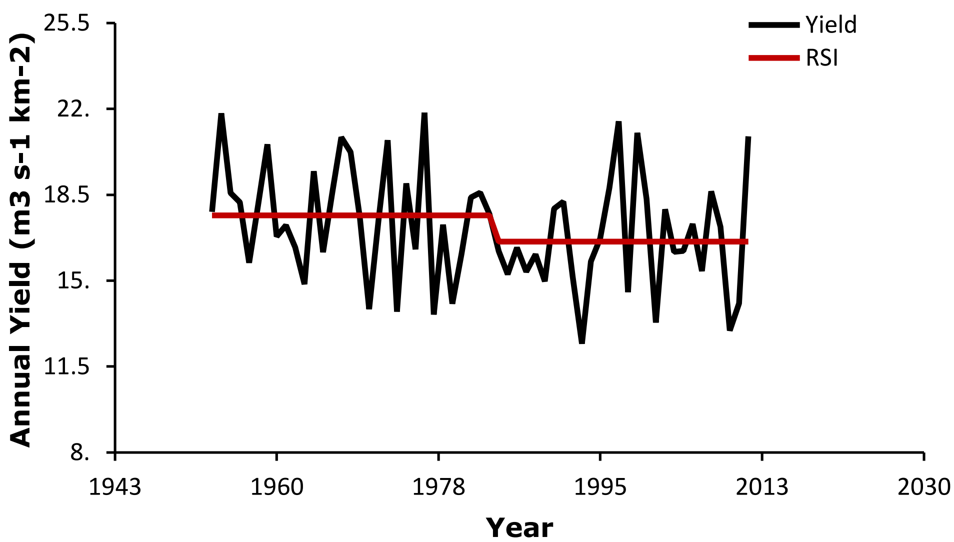


Figure 4.2.19 Regime Shift Indicator test for the Upper West Columbia composite annual yield showing a significant decline in 1984 *p*<0.1

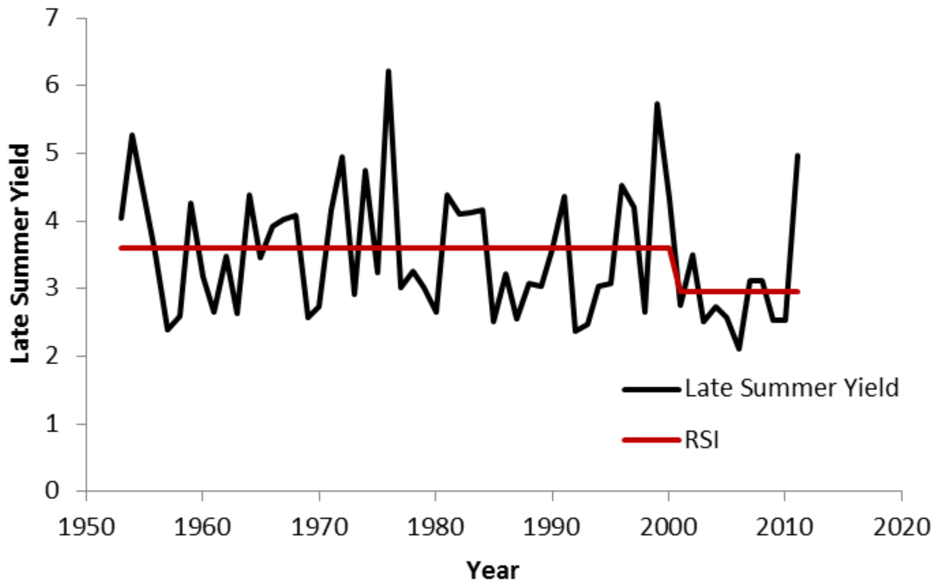


Figure 4.2.20 Regime Shift Indicator test for the Upper West Columbia composite late summer yield showing a significant decline in 2001 *p*<0.05.

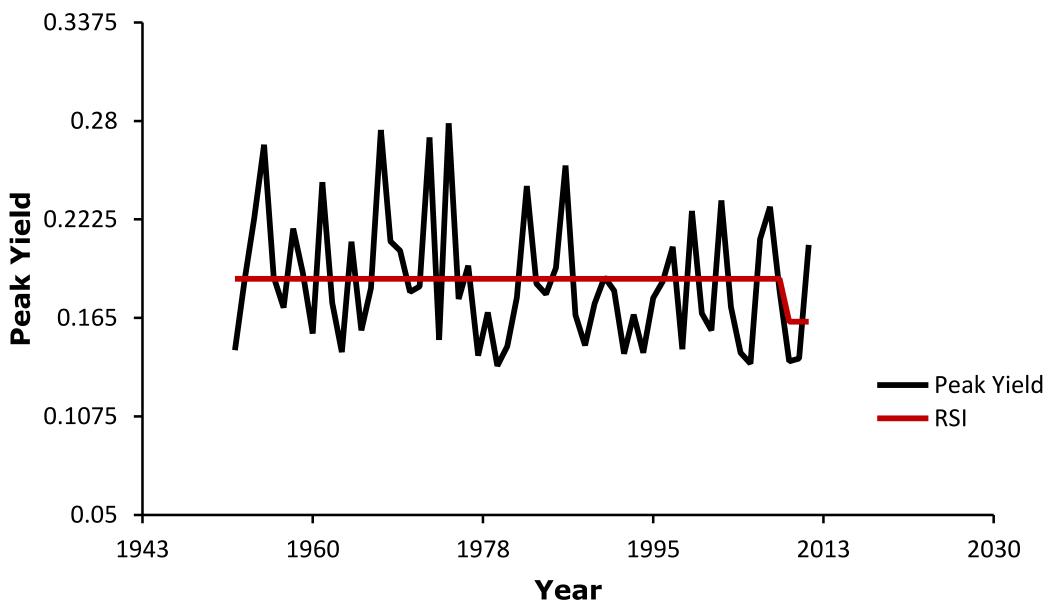


Figure 4.2.21 Regime Shift Indicator test for the Upper West Columbia composite late summer yield showing a non-significant decline in 200p *p*=038.

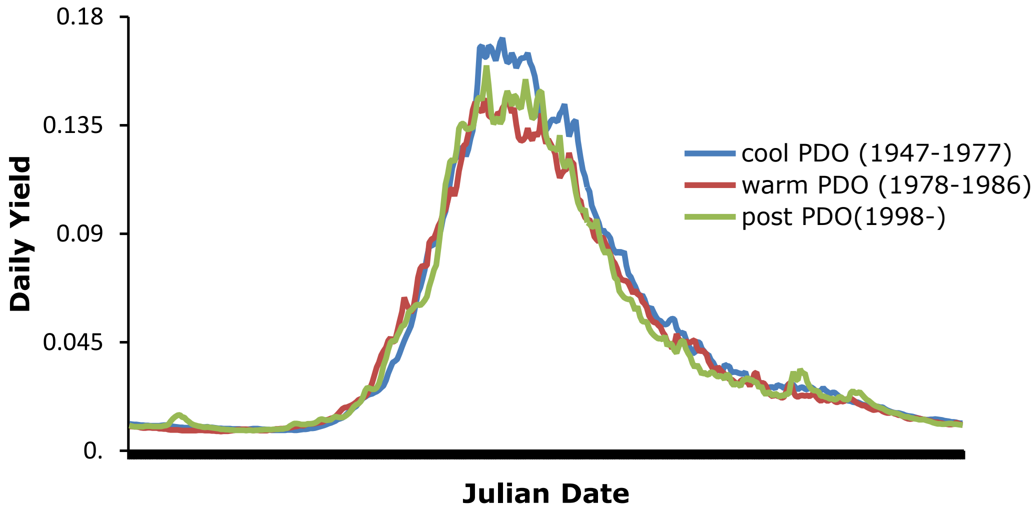


Figure 4.2.22 Hydrograph changes between the three main PDO phases in the last 65 years for the Upper West Columbia composite time series.

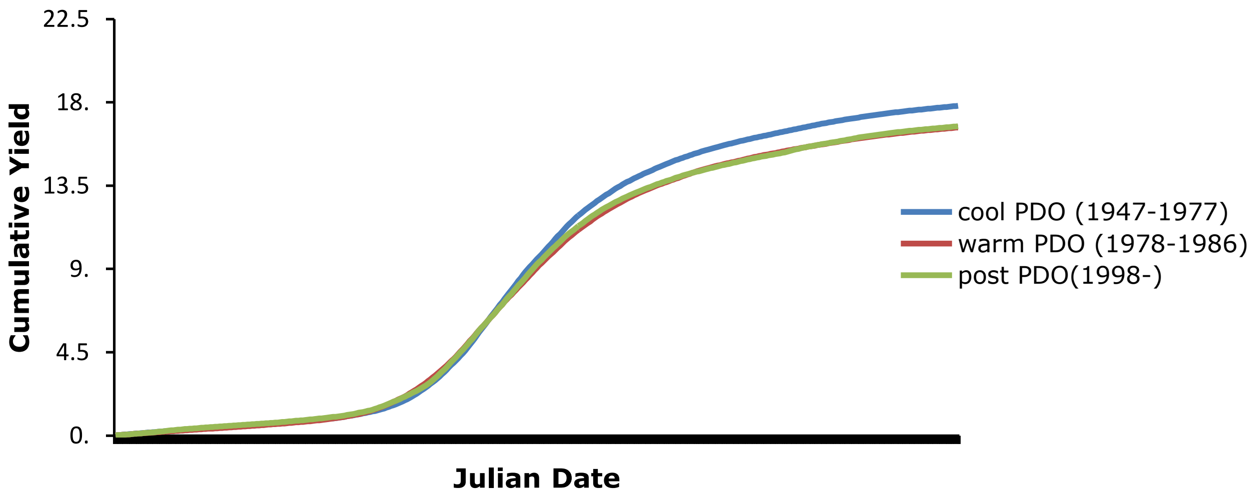


Figure 4.2.23 The cumulative yield for the three main PDO phases in the last 65 years for the Upper West Columbia composite time series.

East Columbia

The East Columbia region covers 17,870 km^2. There are 6 monitored streams in the area and none with greater than 2% glacier cover. All streams showed weak declines in annual yield from 1980 to 2011, averaging -4% (Table 4.2.11). Declines in the late summer minimum yield were greater, and significant for 3 streams, average declines were -18% through this time periods. Declines in peak and maximum yield were also weak and non-significant averaging -8 and -5% respectively. There were no significant changes in timing, though the tendency was for the freshet, date of half volume, and date of maximum flow to have moved forward by 4-8 days. Monthly trends show declines through the year for most streams, in particular in the late summer and fall months (Table 4.2.12).

The regional composite time series and hydrographs for the East Columbia Composite are good representations of the changes occurring in most streams in the region. The correlation matrix of annual yield indicates that the streams in this region are strongly and significantly correlated to the composite trend (Table 4.2.13). The RSI test shows no trend through the period of record for annual yield and the last summer yield (1932-2011)(Figure 4.2.24-4.2.25). The late summer minimum shows a significant decline in 2000 ($p<0.01$), and the peak yield shows a significant decline from 1984 ($p<0.05$) (Figure 4.2.26).

The hydrographs for the main PDO time periods are similar for all stream and show clear declines in the peak and maximum flows, as well as a reduction in the time spent at high flows (Figure 4.2.27). There is some suggestion that the onset of freshet is occurring earlier, though no other temporal parameters show significant change. Comparing the previous cool phase PDO to the present, we see that annual yield has declined significantly by -18% ($p<0.001$), as has the late summer minimum flow by -6% ($p<0.05$), and peak flows by -20% ($p<0.05$).

Table 4.2.11. Changes in flow for individual stream records in the East Columbia from 1980-2011. Stars indicate Mann-Kendall trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Stream	Percent of Catchment Glaciated	Annual Yield %	Winter Min. Yield %	Low flow Yield Sum	Late Summer Min. Yield %	Late Summer Yield Sum %	Onset freshet (days)	Center volume (days)	Date of Max flow (days)	Date of summer Min (days)	Peak Yield	Maximum Yield
Bull	0.08	-1.7	-18.1	4	-4	-2.3	3	9	10	1	-11	-2
Elk	0.73	-1.7	1.3	11	-3*	-7	5	6	9	-1	-14	-18
Mathers	0	-3	19	8	-9	-12	-2	4	5	0	-3	24
Moyie 1	0	-7	-11	-20	-32	-30	8	6	9	-2	-4	12
Moyie 2	0	-14	-25	-29	-54*	-46	1	6	9	-2	-11	9
Flathead	0	-1	-2	11	-8	9	9	7	8	0	-4	-1
St-Mary 1	0.03											
St-Mary 2	0.03	-3	20	8	-30**	-18	-1	3	7	0	-9	12
Average		-4	-2	-1	-16	-15	3	6	8	-1	-8	5
East Composite		-6	-8	-12	-15	-18	7	6	8	1	-5	7

Table 4.2.12. Monthly correlation coefficients for individual streams flow in the East Columbia region from 1980-2011. Bold highlights significant Mann Kendall trends at *p*<0.10, shaded areas highlight negative trends.

Monthly	East Comosite	Bull	Elk	Mathers	Moya a	Moya b	Flathead	St-Mary 1	St-Mary 2
January	-0.05	-0.02	0.09	0.09	-0.05	-0.17	0.02	-0.46	0.30
February	-0.19	-0.12	0.10	-0.08	-0.20	-0.27	-0.02	-0.44	0.28
March	-0.06	-0.01	0.25	0.11	-0.07	0.02	0.01	-0.14	0.30
April	-0.19	-0.23	-0.03	0.00	-0.19	-0.28	-0.35	**0.49**	-0.17
May	-0.08	-0.18	-0.29	0.06	-0.07	-0.23	-0.28	0.04	-0.05
June	0.10	0.11	0.09	0.11	0.09	0.08	0.16	-0.42	0.05
July	-0.07	-0.02	-0.04	0.03	-0.08	-0.13	0.09	-0.28	0.03
August	-0.20	-0.03	-0.10	0.00	-0.26	**-0.37**	0.07	-0.36	-0.16
September	-0.11	0.09	0.10	-0.03	-0.24	**-0.25**	0.08	-0.50	-0.14
October	-0.06	0.12	0.23	0.01	-0.14	-0.18	0.09	-0.42	0.09
November	-0.19	0.02	0.17	0.07	-0.22	-0.08	0.01	-0.18	0.03
December	-0.09	-0.06	0.16	0.13	-0.11	-0.17	0.10	-0.06	0.15

Table 4.2.13 Correlation matrix for streams and the regional composite time series for the East Columbia Region.

	E. Comp.	Bull	Elk	Mathers	Moyie A	Moyie B	Flathead	St-Mary A	St-Mary B
East Composite	1.00								
Bull	0.95	1.00							
Elk	0.84	0.89	1.00						
Mathers	0.94	0.95	0.84	1.00					
Moyie A	0.97	0.93	0.82	0.93	1.00				
Moyie B	0.95	0.93	0.80	0.88	0.95	1.00			
Flathead	0.89	0.89	0.85	0.79	0.89	0.85	1.00		
St-Mary A	0.91	0.92	0.83	0.90	0.90	0.94	0.83	1.00	
St-Mary B	0.89	0.86	0.75	0.86	0.89	0.89	0.83	0.97	1.00

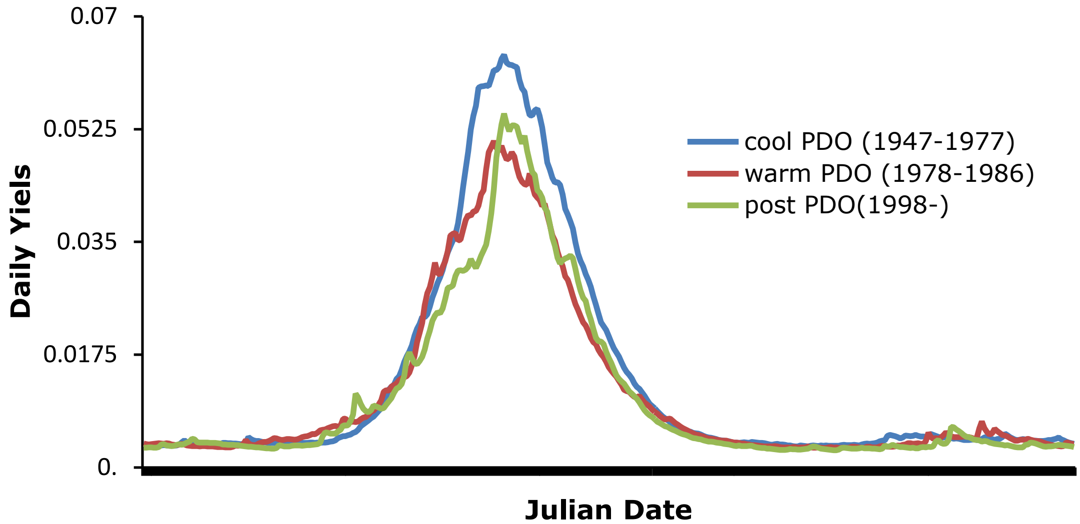


Figure 4.2.27 Hydrograph changes between the three main PDO phases in the last 65 years for the East Columbia composite time series.

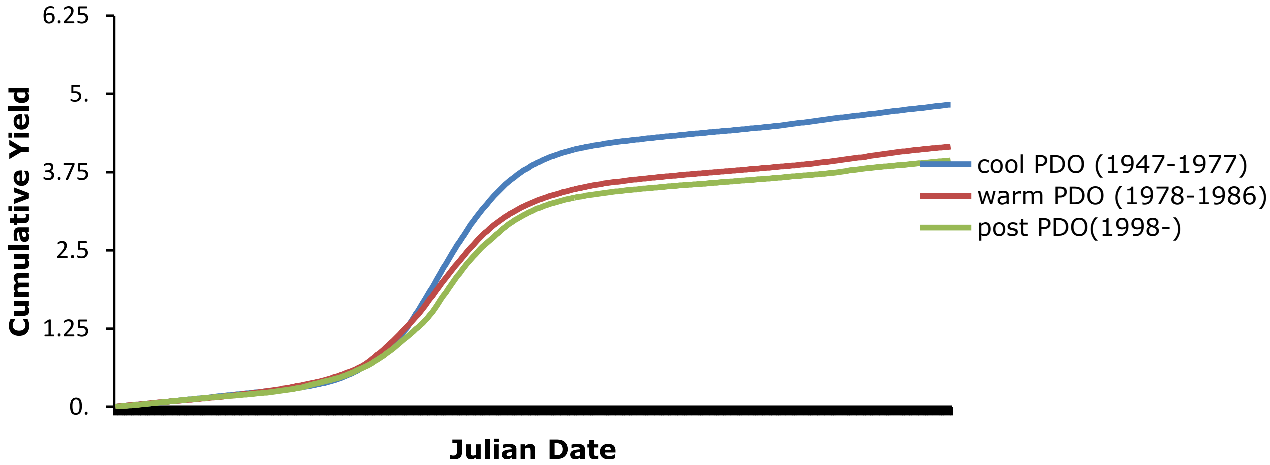


Figure 4.2.28 The cumulative yield for the three main PDO phases in the last 65 years for the East Columbia composite time series

West Columbia

The West Columbia region encompasses 10,373 km^2. There are five monitored streams, with only one stream having greater than 2% in glacier area (Slocan River) (Table 4.2.1). All streams show non-significant declines since 1980 by an average of -10% and 4 of 5 show significant declines in the late summer minimum, with an average decline of- 29%, and 2 the late summer volume of flow with an average decline of -30% (Table 4.2.14). Max flow declined in 3 of 5 streams by an average of -6%, and there were no significant changes in the timing of flow. The regional composite showed a significant decline in both the annual yield and in the late summer minimum. Monthly trends show declines through the year, particularly in the late summer-early fall (Table 4.2.15).

The regional composite time series and hydrograph are good representations of the changes occurring in all the streams in the West Columbia region. A correlation matrix of annual yield indicates that all the streams in this region are strongly and significantly correlated (Table 4.2.16). The RSI test indicates a significant decline in annual yield in 1973 (p<0.0001), and a non-significant decline in 2009 (p=0.27) (Figure 4.2.29). The late summer yield showed a significant decline from 1985 (p<0.001) (Figure 4.2.30), and the late summer minimum yield in 1992 (p<0.0001). Peak yield showed significant decline in 1975 (p<0.005), and a non-significant decline in 2010 (p=0.40)(Figure 4.2.31).

The regional composite hydrographs well represent the changes observed in all streams across the main PDO periods. In the West Columbia region we see large declines in maximum flow and large reductions in late summer to fall flow (Figure 4.2.32). The date of half volume has shifted to an earlier date; however the onset of freshet has not. In comparing the previous cool phase PDO to the present, we see significant declines in annual yield by -19% (p<0.001) (Figure 4.2.33), the late summer minimum by -40% (p<0.001), maximum flow by -14% (p<0.05), the low flow volume by -7% (p<0.05), the late summer flow volume by -34% (p<0.001), and the date of half volume by -3 days (p<0.05).

Table 4.2.14 Changes in flow for individual stream records in the West Columbia from 1980-2011. Stars indicate Mann-Kendall trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Stream	Percent of Catchment Glaciated	Annual Yield %	Winter Min. Yield %	Low flow Yield Sum	Late Summer Min. Yield %	Late Summer Yield Sum %	Onset freshet (days)	Center volume (days)	Date of Max flow (days)	Date of summer Min (days)	Peak Yield	Maximum Yield
Barnes	0	-8.6	-3.3	-18*	-43**	-38**	6	1	9	2	2	3
Inonoaklin	0	-20	6.5	-20*	-67**	-75**	-1	-3	15	2	-2	9
Slocan	0.07	-7	-2	-6	-22*	-12	0	3	9	-2	-12	-12
Kaslo	0.56	-8	-6	1	-13	-9	4	3	18	0	-16	-20
Lardeau	1.01	-4	-1	15	-2*	-16	-1	0	8	-2	-15	-12
Average		-10	-1	-6	-29	-30	2	1	12	0	-9	-6
West Composite		-15*	-4	-7	-35**	-30	3	-1	6	-1	-15	-15

Table 4.2.15. Monthly correlation coefficients for individual streams flow in the West Columbia region from 1980-2011. Bold highlights significant Mann Kendall trends at *p*<0.10, shaded areas highlight negative trends.

Monthly	West Composite	Barnes	Inon.	Slocan	Kaslo	Lardeau
January	-0.10	-0.08	-0.08	-0.03	-0.12	0.03
February	-0.10	-0.04	-0.07	-0.10	-0.15	0.08
March	-0.20	-0.23	-0.12	-0.19	-0.11	0.04
April	-0.17	-0.23	-0.08	-0.17	-0.20	0.01
May	-0.17	-0.07	-0.05	-0.12	-0.20	0.00
June	-0.14	0.09	-0.01	0.03	-0.04	-0.04
July	-0.29	-0.26	-0.44	-0.10	-0.08	-0.13
August	**-0.40**	**-0.36**	**-0.53**	-0.18	-0.13	-0.25
September	**-0.35**	**-0.30**	-0.23	*-0.23*	-0.17	-0.16
October	-0.12	**-0.32**	-0.30	-0.08	-0.04	0.25
November	-0.18	-0.29	-0.29	-0.14	-0.10	0.10
December	-0.15	-0.19	-0.22	-0.09	-0.14	0.06

Table 4.2.16 Correlation matrix for streams and the regional composite time series for the West Columbia Region.

	W. Comp.	*Barnes*	*Inonoaklin*	*Kaslo*	*Lardeau*	*Slocan*
West Composite	1.00					
Barnes	0.88	1.00				
Inonoaklin	0.91	0.94	1.00			
Kaslo	0.95	0.87	0.87	1.00		
Lardeau	0.81	0.76	0.67	0.89	1.00	
Slocan	0.79	0.91	0.90	0.96	0.89	1.00

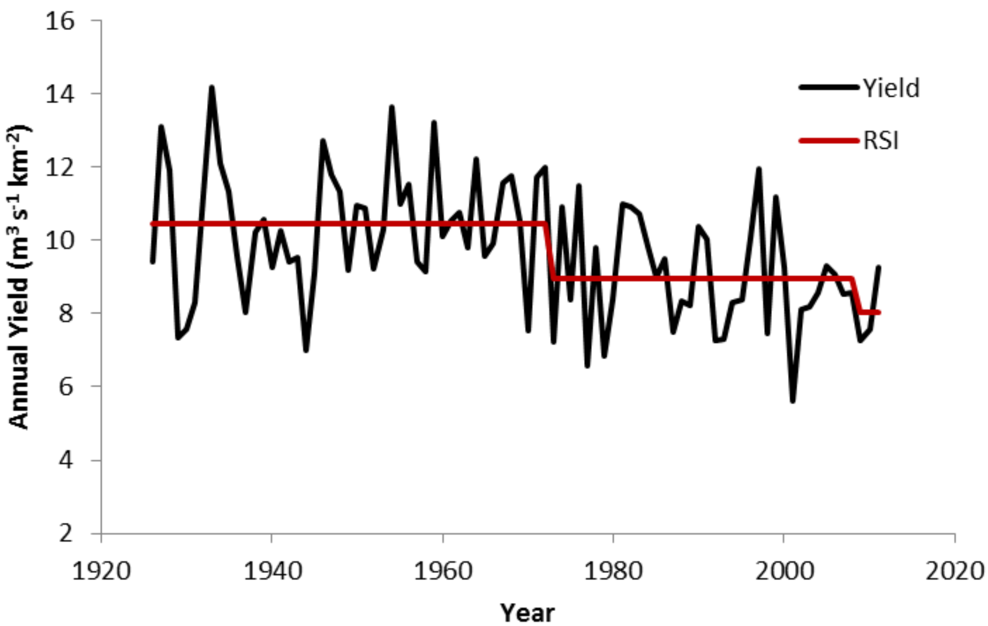


Figure 4.2.29 Regime Shift Indicator test for the West Columbia composite annual yield showing a significant decline in 1973 *p*<0.0001, and a non-significant decline in 2009 *p*=0.27.

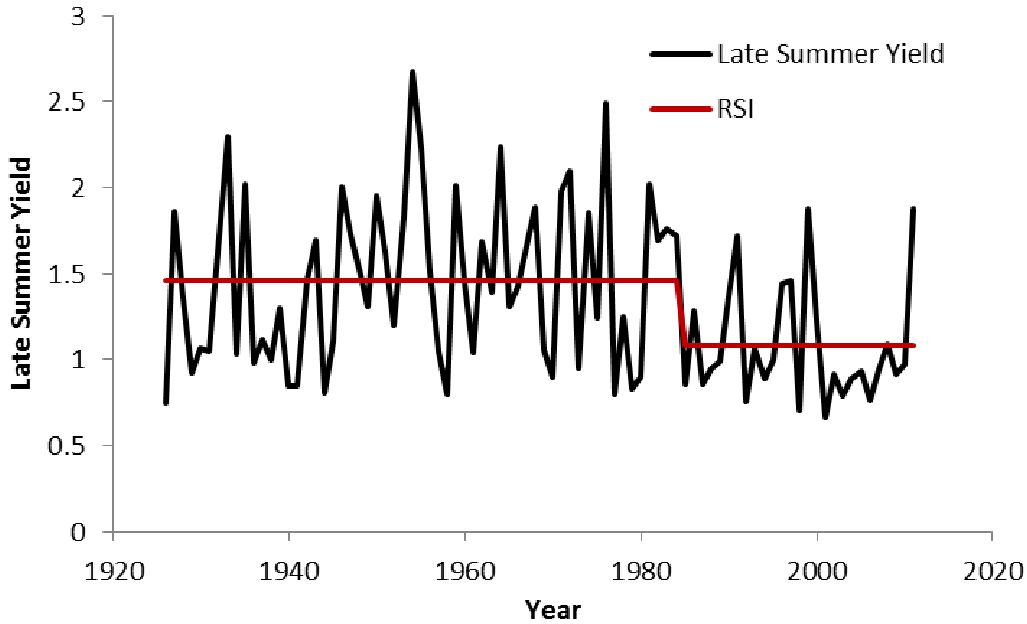
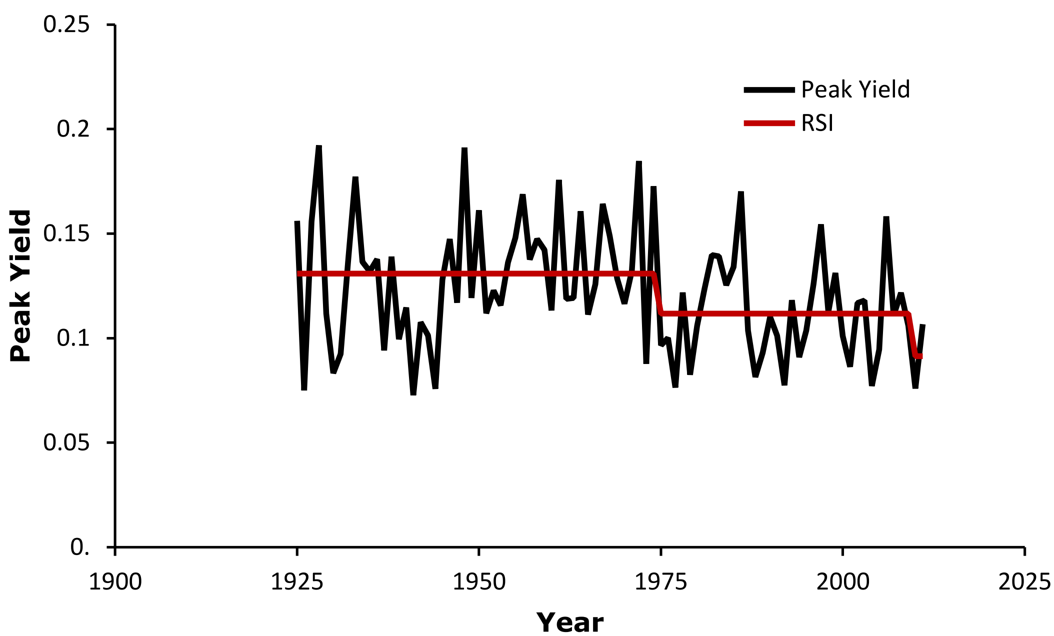
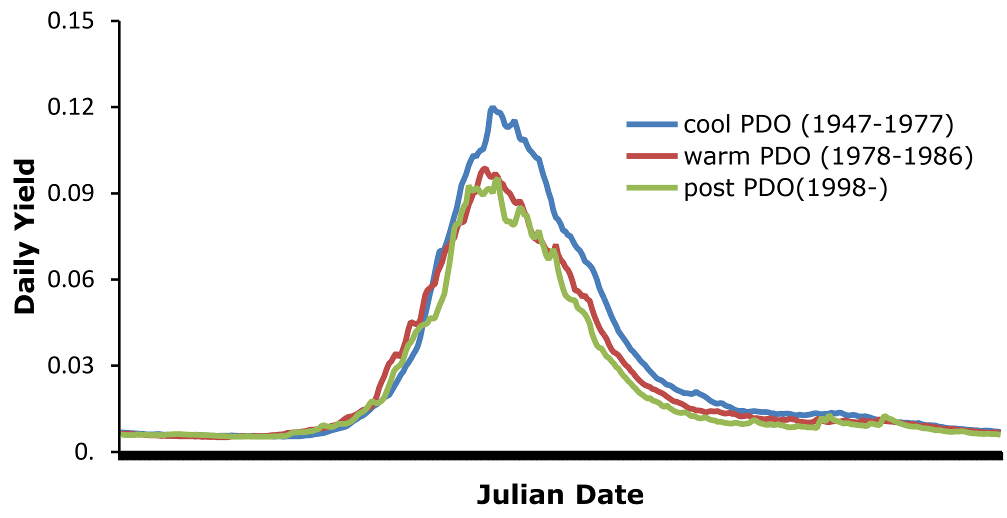


Figure 4.2.30 Regime Shift Indicator test for the Upper East Columbia composite late summer yield showing a significant decline in 1985 *p*<0.0005.



4.2.31 Regime Shift Indicator test for the West Columbia composite peak yield showing a significant decline in 1975 (*p*<0.005), and a non-significant decline in 2010 (*p*=0.40).



4.2.32 Hydrograph changes between the three main PDO phases in the last 65 years for the West Columbia composite time series.

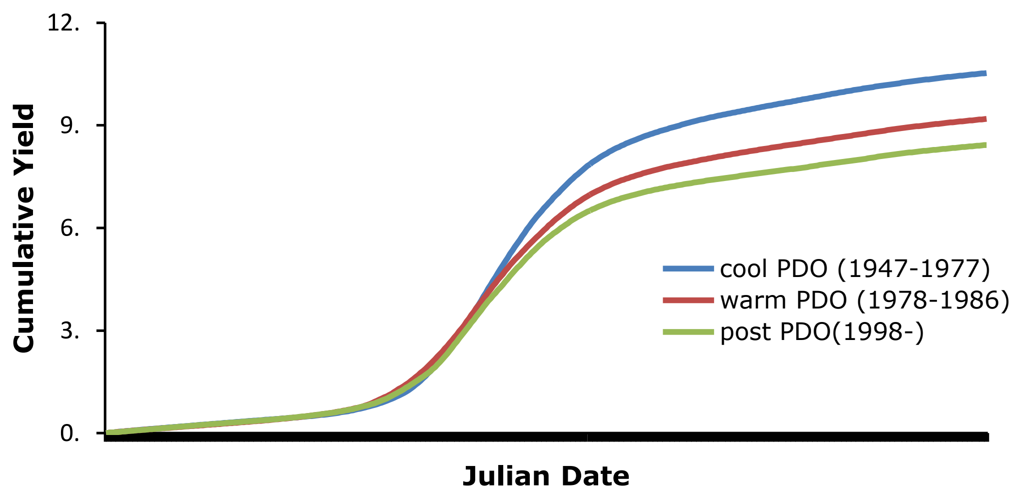


Figure 4.2.33 The cumulative yield for the three main PDO phases in the last 65 years for the West Columbia composite time series.

Lower Columbia

The Lower Columbia composite region covers area of 8,536 km^2. There are 10 monitored streams in this region, none with significant glaciation (Table 4.2.1). Seven of the ten streams show non-significant declines in yield since 1980 by an average of -11% (Table 4.2.17), and 5 streams show significant declines in the late summer minimum by an average of -32%. There were no significant changes in the timing of flow though there was a tendency for the date of half volume, maximum flow and the onset of freshet to have moved later in the year. Looking at the results on a monthly time scale

we see declines in most months apart from June, with particularly strong declines from July to December in many streams (Table 4.2.18).

The regional composite time-series for the Lower Columbia region is a good representation of the flow metrics in all streams in the region. A correlation matrix of annual yield indicates that all streams are strongly and significantly correlated to the Lower Columbia Composite time-series (Table 4.2.19). The RSI rest indicated a significant decline in annual yield in 2001 ($p<0.1$) (Figure 4.2.34). The late summer yield and minimum yield indicated a significant increase in 1971 ($p<0.005$), followed by a significant decrease in 2000 ($p<0.05$)(Figure 4.2.35). Peak yields decreased in 2004, though confidence is quite low ($p=0.60$) (Figure 4.2.36).

The composite hydrograph shows the regional average, and is not necessarily representative of each monitored stream in the region. The hydrographs for Deer, Anderson, and Salmo streams in the Lower Columbia region show relatively little change, whereas Sullivan, Big Sheep, Arrow, and Boundary Creeks show little change in the timing of flow, but do show a reduction in the annual yield. Duck Creek stands out as showing significant declines in the most parameters. In evaluating the Lower Columbia Composite time series, we see small changes in maximum flow and annual yield (Figure 4.2.37, 4.2.38). Comparing the previous cool PDO to the current cool phase PDO we see significant reductions in the annual yield and maximum by -11 and -13% ($p<0.05$).

Table 4.2.17 Changes in flow for individual stream records in the Lower Columbia from 1980-2011. Stars indicate Mann-Kendall trend significance with * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Stream	Percent of Catchment Glaciated	Annual Yield %	Winter Min. Yield %	Low flow Yield Sum	Late Summer Min. Yield %	Late Summer Yield Sum %	Onset freshet (days)	Center volume (days)	Date of Max flow (days)	Date of summer Min (days)	Peak Yield	Maximum Yield
Duck	0	0	-7	-1	-12	-11	13	5	0	2	-1	-3
Sullivan	0	3	-30**	-18	-10	-4	7	9	18	1	30	50
Big Sheep	0	-24	-7	-36	-50**	-62*	7	1	2	4	-21	-15
Grandby	0	-12	-3	-29	-55**	-53*	-16	3	6	-1	-16	-13
Kettle	0	-17	-23	-37	-69***	-62**	8	0	5	0	-11	-14
Arrow	0	-1	-16*	-8	-4	-14	6	4	8	1	-12	1
Boundary	0	-12	-23	-23*	-43	-40	3	5	9	4	-9	-7
Salmo	0	-9	-14	-19	-41*	-33	9	4	7	5	-9	-13
Anderson	0	-11	-18	-20	-52***	-32	10	3	1	2	-3	10
Deer	0	7	-2.4	7	-21	-23	4	0	7	0	-1	-7
Average		-8	-14	-18	-36	-33	5	3	6	2		-1
Lower Composite		-11	-16	-20	-32*	-31	7	4	6	0	-10	-11

Table 4.2.18. Monthly correlation coefficients for individual streams flow in the Lower Columbia region from 1980-2011. Bold highlights significant Mann Kendall trends at *p*<0.10, shaded areas highlight negative trends.

Monthly	Lower Composite	Duck	Sullivan	Big Sheep	Grandby	Kettle	Arrow	Boundary	Salmo	Anderson	Deer
January	-0.15	-0.06	-0.22	-0.16	0.02	**-0.22**	-0.10	-0.13	-0.07	-0.07	0.04
February	-0.25	-0.18	**-0.35**	-0.24	-0.14	-0.12	-0.18	-0.19	-0.20	-0.23	0.06
March	-0.24	-0.20	**-0.18**	-0.31	-0.30	-0.31	-0.06	-0.15	-0.16	-0.23	-0.12
April	-0.25	-0.18	**-0.28**	-0.21	-0.14	-0.15	-0.26	-0.28	-0.18	-0.18	0.03
May	-0.06	-0.03	0.05	-0.06	-0.02	-0.05	-0.05	-0.02	-0.01	0.02	0.19
June	0.05	0.10	0.20	-0.11	0.05	0.02	0.08	0.16	0.08	-0.09	0.17
July	-0.20	-0.07	-0.01	**-0.42**	-0.26	-0.35	-0.01	-0.16	-0.16	-0.18	-0.21
August	**-0.33**	-0.18	-0.20	**-0.48**	**-0.35**	**-0.45**	-0.18	-0.40	-0.30	**-0.39**	-0.15
September	**-0.29**	-0.15	**-0.37**	**-0.29**	**-0.22**	**-0.38**	-0.12	**-0.19**	**-0.24**	**-0.28**	-0.12
October	-0.23	0.10	-0.31	**-0.18**	**-0.32**	**-0.40**	-0.14	-0.21	-0.21	**-0.24**	-0.12
November	-0.29	-0.06	-0.35	-0.28	**-0.33**	**-0.40**	-0.22	-0.30	-0.20	**-0.26**	-0.12
December	-0.14	-0.07	-0.19	-0.15	-0.13	**-0.25**	-0.13	-0.11	-0.06	**-0.16**	-0.06

Table 4.2.19 Correlation matrix for streams and the regional composite time series for the Lower Columbia Region.

	LComp	Duck	Sullivan	Big Sheep	Granby	Kettle	Arrow	Anderson	Boundary	Deer	Salmo
Lower Composite	1.00										
Duck	0.94	1.00									
Sullivan	0.90	0.84	1.00								
Big Sheep	0.91	0.77	0.80	1.00							
Granby	0.95	0.88	0.81	0.95	1.00						
Kettle	0.87	0.65	0.80	0.87	0.96	1.00					
Arrow	0.93	0.92	0.82	0.78	0.84	0.71	1.00				
Anderson	0.94	0.91	0.77	0.86	0.90	0.86	0.88	1.00			
Boundary	0.89	0.81	0.85	0.80	0.86	0.70	0.87	0.86	1.00		
Deer	0.89	0.87	0.81	0.82	0.89	0.87	0.78	0.88	0.75	1.00	
Salmo	0.93	0.85	0.81	0.87	0.94	0.84	0.90	0.91	0.93	0.83	1.00

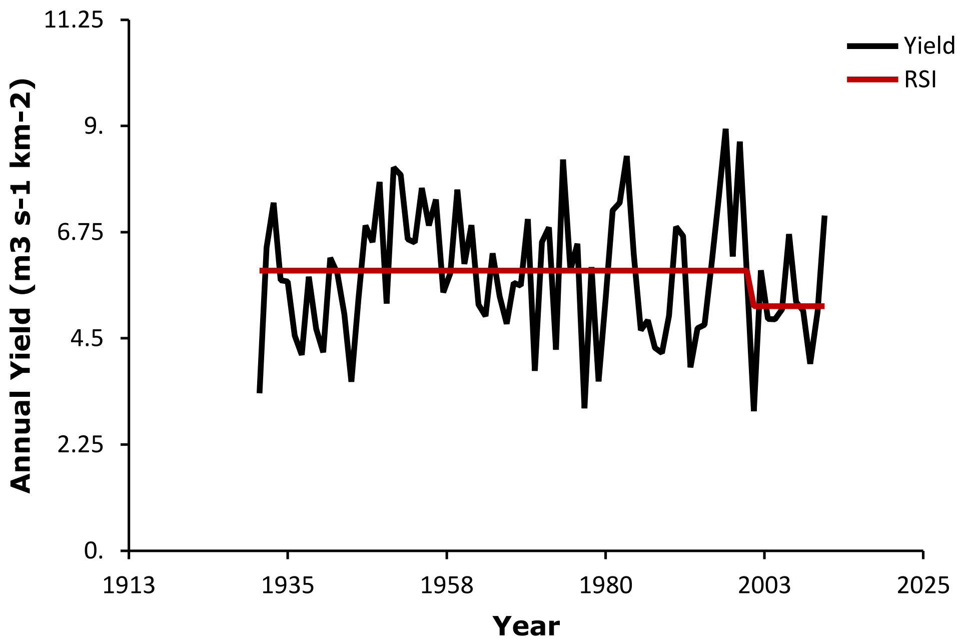


Figure 4.2.34 Regime Shift Indicator test for the Lower Columbia composite annual yield showing a significant decline in 2001 *p*<0.1.

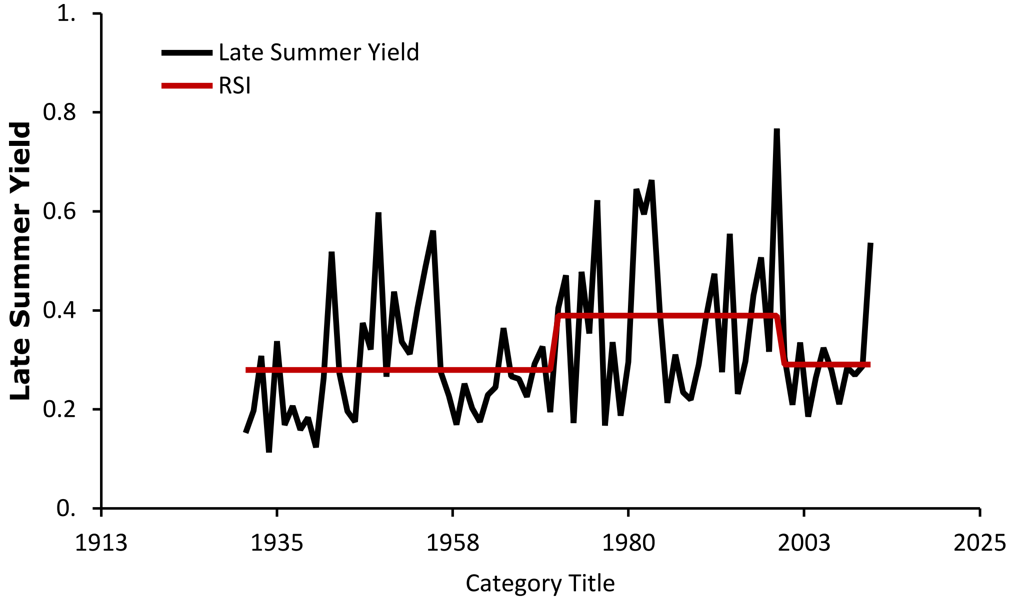


Figure 4.2.35 Regime Shift Indicator test for the Lower Columbia composite late summer yield showing a significant increase in 1971 (*p*<0.005), followed by a decline in 2000 (*p*<0.05.)

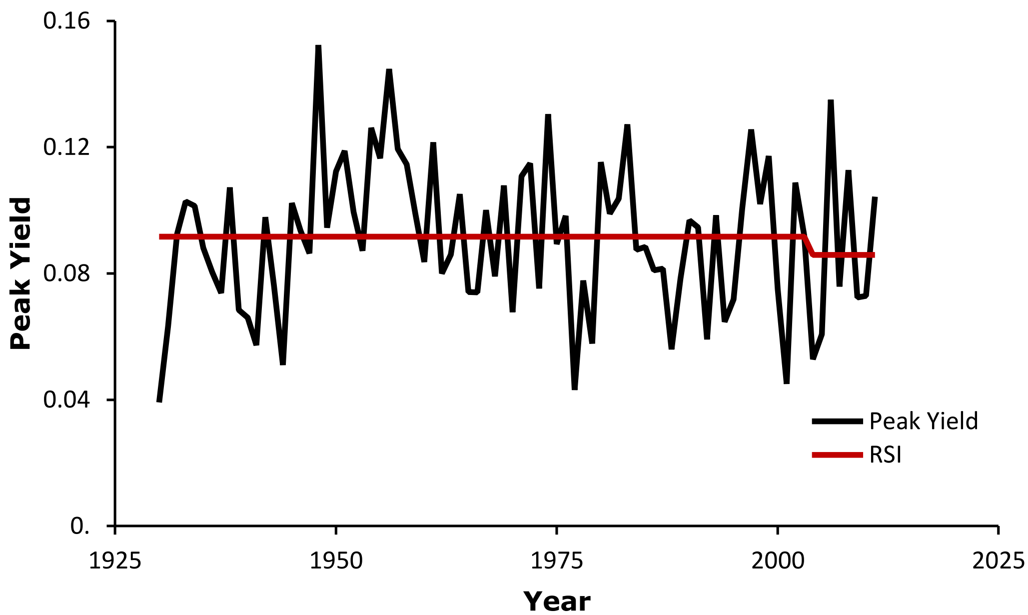


Figure 4.2.36 Regime Shift Indicator test for the Lower Columbia composite peak yield showing a non-significant decline in 2004 (*p*<0.60).

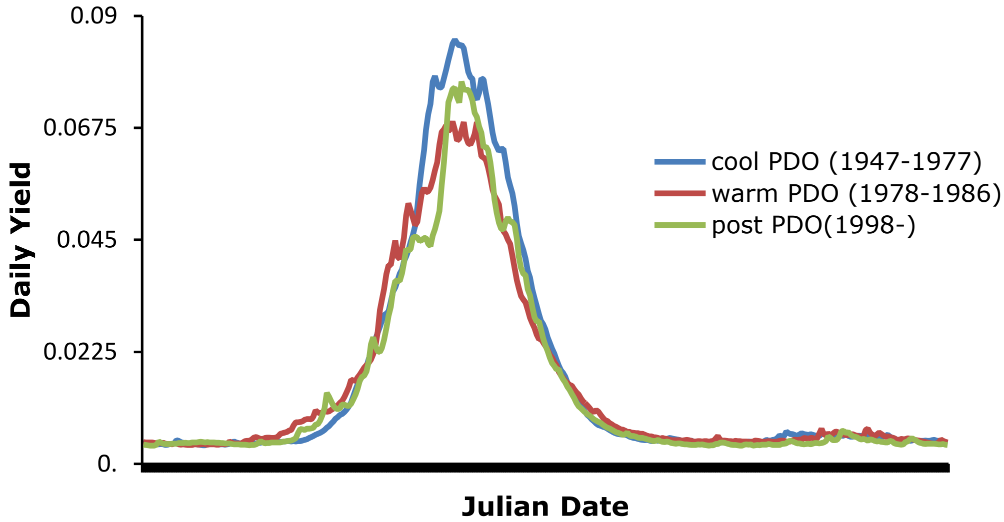


Figure 4.2.37 Hydrograph changes between the three main PDO phases in the last 65 years for the Lower Columbia composite time series.

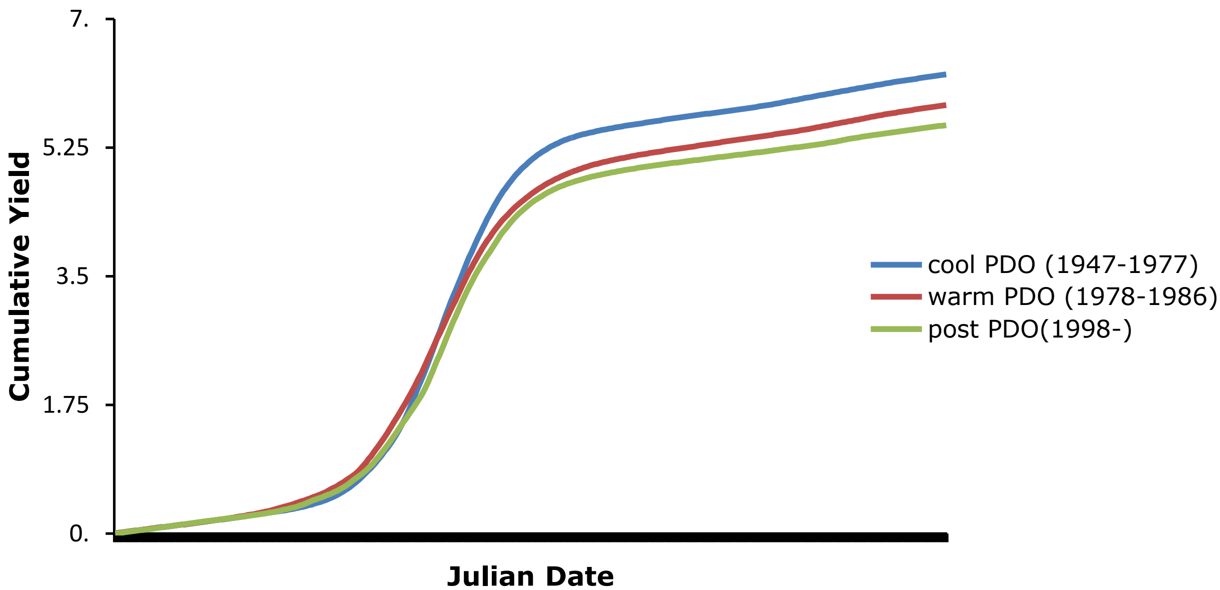


Figure 4.2.38 The cumulative yield for the three main PDO phases in the last 65 years for the Lower Columbia composite time series.

Residual Trends

Because the PDO, ENSO, and NOI exert a significant influence on steam flow in the Columbia Basin, we removed these time-series from the annual yield to observe the remaining (residual) time series. All residual time series, apart from the Lower Columbia, show declines in recent decades. The Upper East, East and West Columbia regions were significant using Mann-Kendall trend analysis at $p<0.01$, $p<0.1$, and $p<0.001$ respectively (Figure 5.39-5.43).

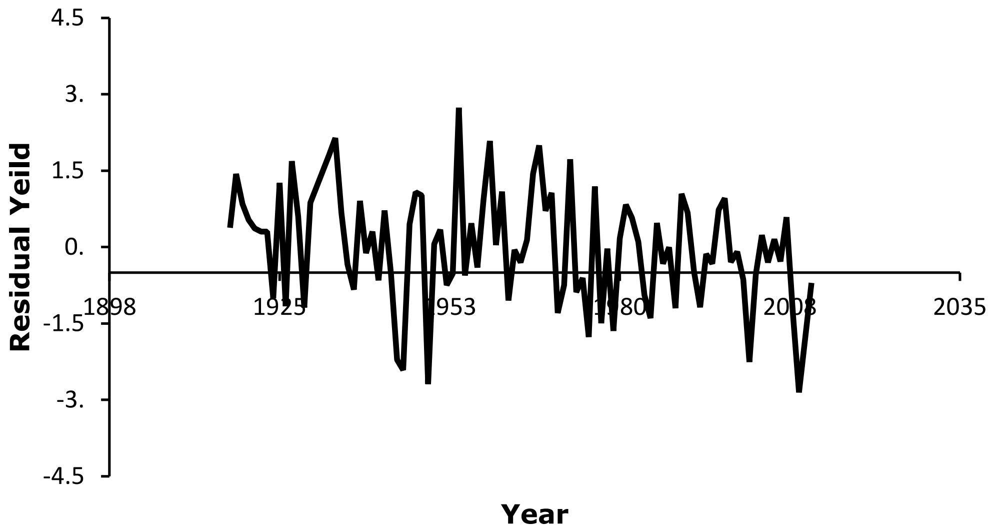


Figure 4.2.39 Residual Annual Yield in the Upper East Columbia Composite after removing the PDO, NOI, and ENSO trends. The trends shows a significant decline Mann Kendall *p*<0.01.

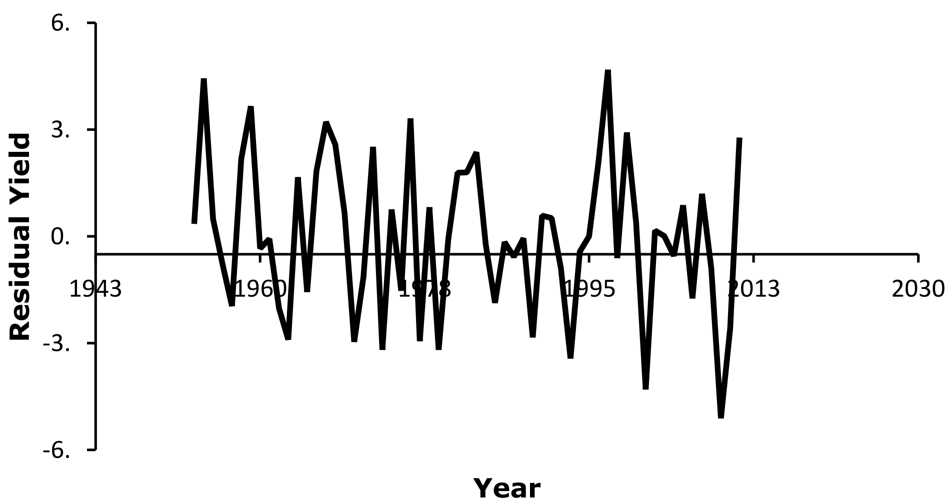


Figure 4.2.40 Residual Annual Yield in the Upper West Columbia Composite after removing the PDO, NOI, and ENSO trends.

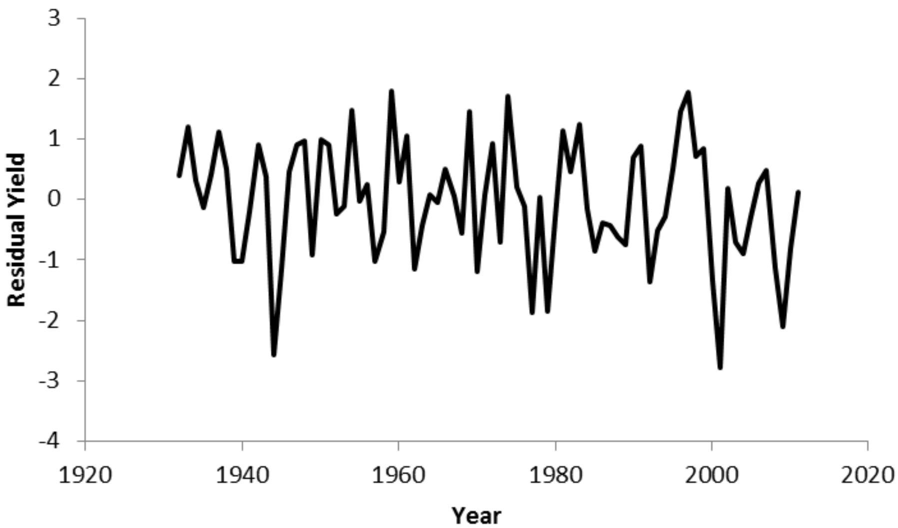


Figure 4.2.41 Residual Annual Yield in the East Columbia Composite after removing the PDO, NOI, and ENSO trends. The trends shows a significant decline Mann Kendall *p*<0.1.

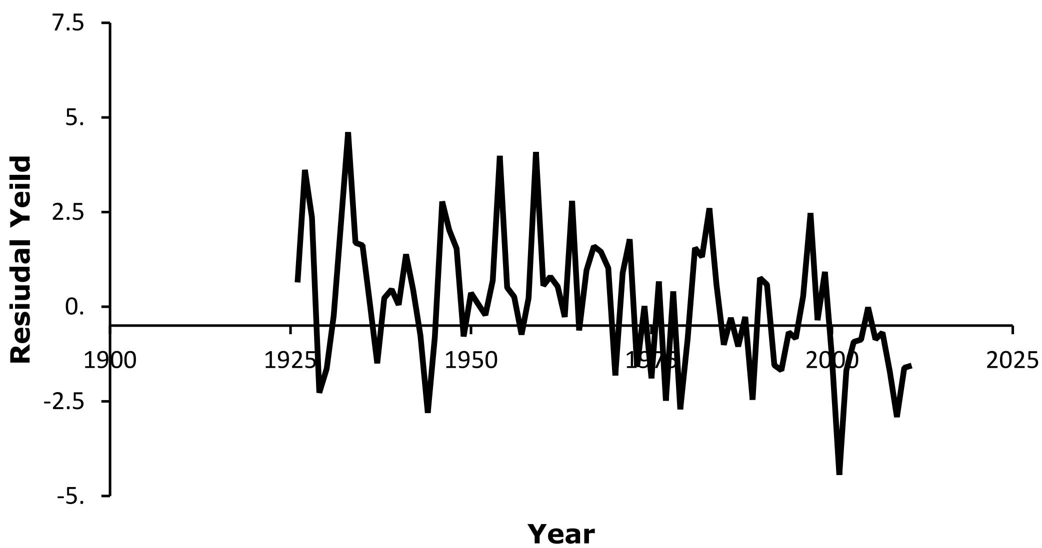


Figure 4.2.42 Residual Annual Yield in the West Columbia Composite after removing the PDO, NOI, and ENSO trends. The trends shows a significant decline Mann Kendall *p*<0.001.

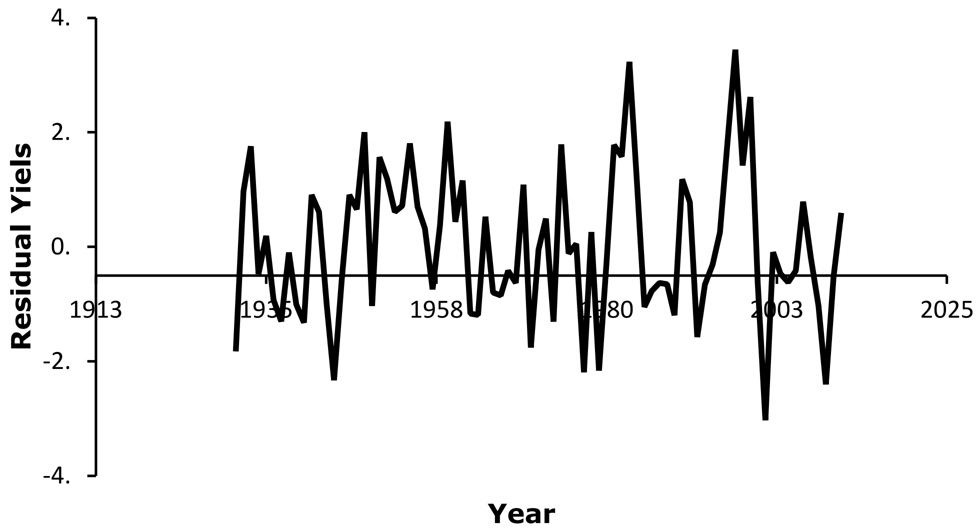


Figure 4.2.43 Residual Annual Yield in the Lower Columbia Composite after removing the PDO, NOI, and ENSO trends.

Streamflow Comparisons to Regional Precipitation

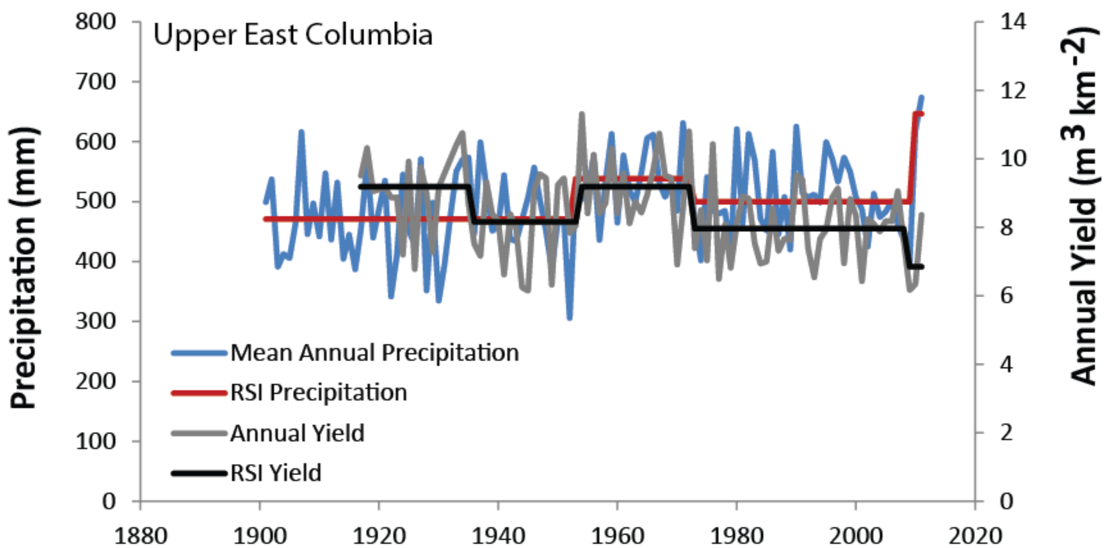


Figure 4.2.44 Historical precipitation (black) shown alongside the average stream yield for the Upper East Columbia Region (gray)

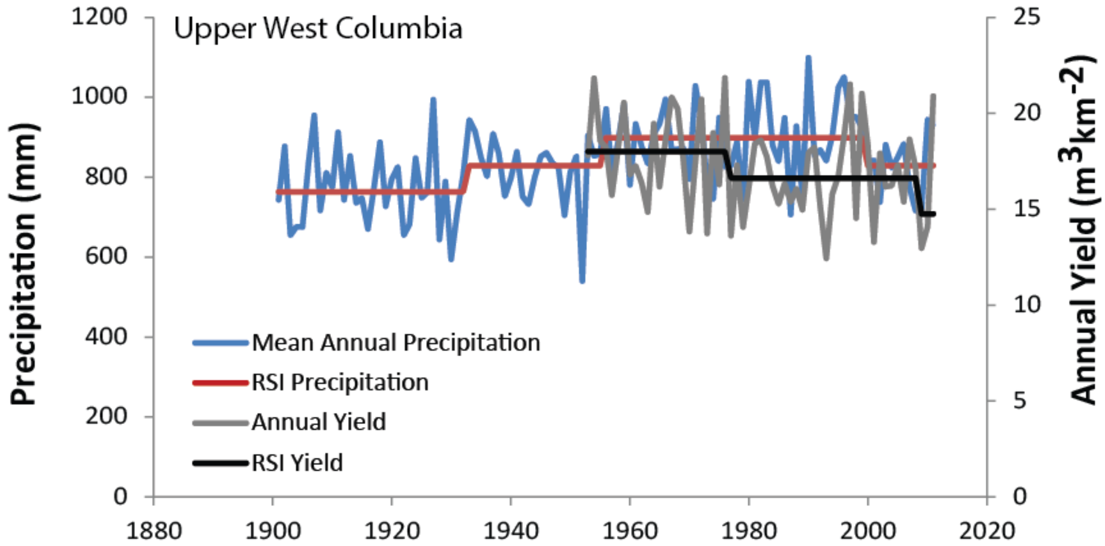


Figure 4.2.45 Historical precipitation (black) shown alongside the average stream yield for the Upper West Columbia Region (gray)

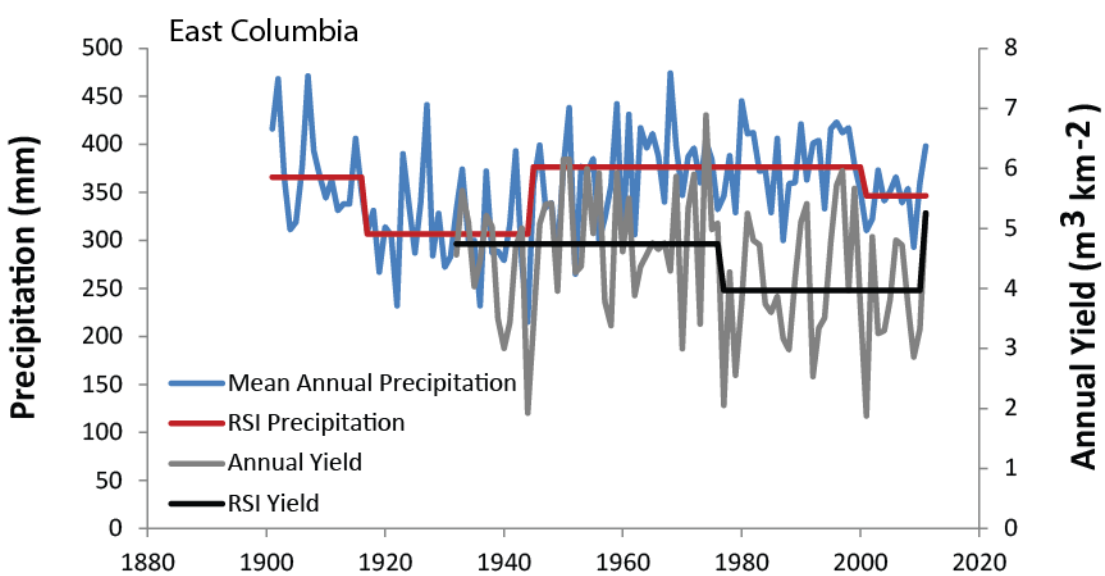


Figure 4.2.46 Historical precipitation (black) shown alongside the average stream yield for the East Columbia Region (gray).

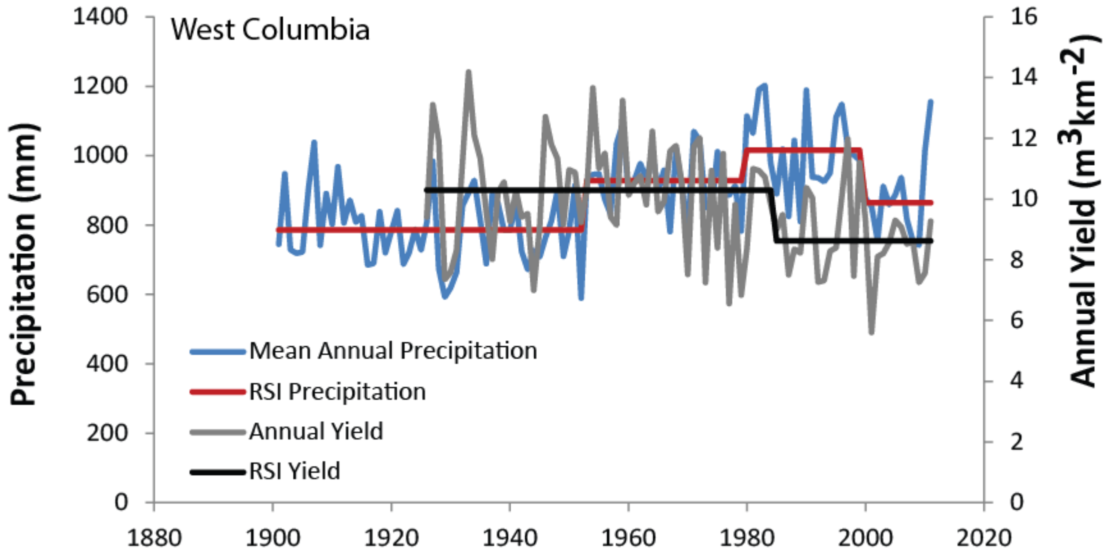


Figure 4.2.47 Historical precipitation (black) shown alongside the average stream yield for the West Columbia Region (gray).

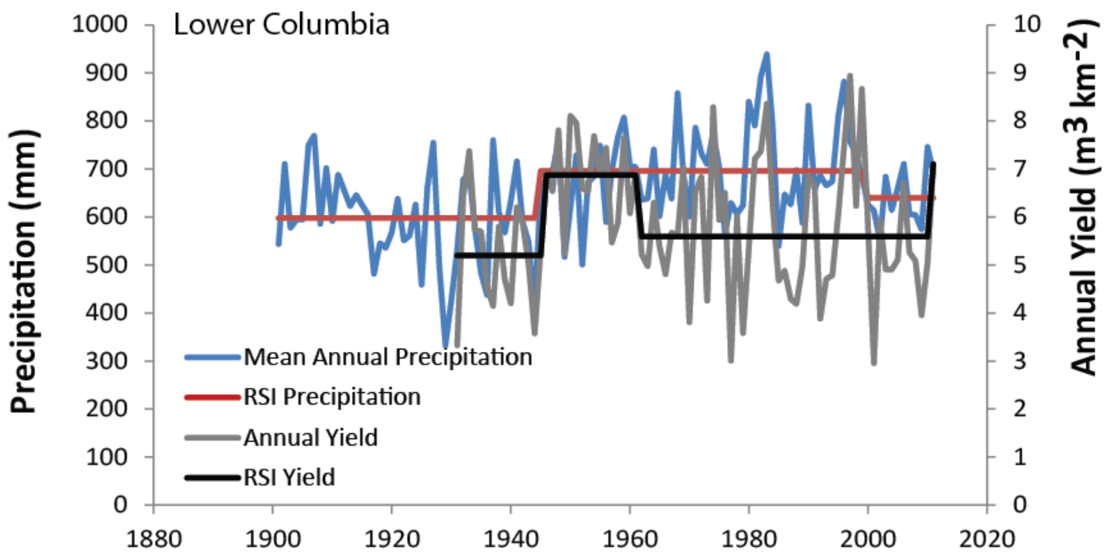


Figure 4.2.48 Historical precipitation (black) shown alongside the average stream yield for the Lower Columbia Region (gray).

Regional Correlation to Temperature indices

There are strong and significant negative relationships between mean annual temperature, mean spring temperature and the degree days over 18 for most hydrometric variables (Table 4.2.20). There are a few regional differences with respect to magnitude and significance, but generally the trends show similar directionality. Correlations were most significant for the late summer metrics, the annual and maximum yields, as well as the onset of freshet, date of peak flow, and center volume.

From a monthly perspective, we see strong positive relationships between mean monthly temperate and flow, accounting for 40% of the variability in April and May flow in the Upper East Columbia, 39-55% in the Upper West Columbia, 14-28% in the East Columbia, 43-60% in the West Columbia, and 28-38% in the Lower Columbia (Table 4.2.21-4.2.25). Mean monthly temperature is significantly negatively related to late summer and fall yield in all regions but the Upper East Columbia. The influence of temperature intensity, as evaluated through the relationship of yield to degree days over 18^0C, is significantly negative for June through November flows, with stronger negative relationships post 1980. In the Upper East Columbia temperature intensity explains 24% of July and August yield, 24-41% of June through August yield in the Upper West Columbia, 14-32% in the East Columbia, 17-47% in the West Columbia, and 8-38% in the Lower Columbia region.

Table 4.2.20 Correlation coefficients for regional stream hydrometric to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001.**

Upper East Columbia	Annual Yield	Winter Min	Low flow Volume	Late Summer Min	Late Summer Volume	Onset freshet	Center volume	Date of Peak flow	Date of summer Min	Peak Flow	Maximum Flow
Mean Spring Temp	-0.31***	-0.01	-0.08	-0.40***	-0.54***	-0.45***	-0.43***	-0.43***	-0.13	-0.43***	-0.35***
Mean Annual Temp	-0.14	0.05	-0.16	-0.24**	-0.32**	-0.42***	-0.28**	-0.26**	-0.16	-0.21**	-0.16
Degree Days >18°C	-0.10	-0.05	0.03	-0.16	-0.18	-0.17*	-0.25**	-0.23**	0.06	-0.04	-0.04
Upper West Columbia											
Mean Spring Temp	-0.42***	-0.05	-0.16	-0.55***	-0.52***	-0.56***	-0.53***	-0.36***	0.05	-0.48***	-0.43***
Mean Annual Temp	-0.20	-0.01	-0.08	-0.25*	-0.31**	-0.38***	-0.36**	-0.13	0.01	-0.24*	-0.23*
Degree Days >18°C	-0.27**	-0.02	0.11	-0.39***	-0.48***	-0.18	-0.50***	-0.21	0.01	-0.03	-0.10
East Columbia											
Mean Spring Temp	-0.38***	-0.05	-0.17	-0.30**	-0.31***	-0.45***	-0.46***	0.02	0.07	-0.39***	-0.38***
Mean Annual Temp	-0.32***	-0.03	-0.22*	-0.30**	-0.32***	-0.30**	-0.27**	-0.03	0.12	-0.29**	-0.22**
Degree Days >18°C	-0.24**	-0.08	-0.13	-0.42***	-0.38***	-0.14	-0.16	0.11	0.01	-0.14	-0.11
West Columbia											
Mean Spring Temp	-0.32***	0.05	-0.18*	-0.46***	-0.55***	-0.52***	-0.65***	-0.60***	0.07	-00.34***	-0.30**
Mean Annual Temp	-0.30**	0.17	-0.17	-0.42***	-0.45***	-0.37***	-0.46***	-0.41***	0.11	-0.30**	-0.27**
Degree Days >18°C	-0.32***	0.01	-0.06	-0.53***	-0.51***	-0.20*	-0.42***	-0.25**	0.17	-0.04	-0.03
Lower Columbia											
Mean Spring Temp	-0.31***	-0.08	-0.19*	-0.19*	-0.28**	-0.42***	-0.65***	-0.59***	0.15	-0.32***	-0.28**
Mean Annual Temp	-0.22*	-0.03	-0.20*	-0.20**	-0.23**	-0.32***	-0.39***	-0.29**	0.13	-0.26**	-0.20*
Degree Days >18°C	-0.25**	-0.14	-0.16	-0.47***	-0.49***	-0.12	-0.25**	-0.13	0.09	-0.15	-0.19*

Table 4.2.21 Correlation coefficients for the Upper East Columbia yields to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001. Bold highlights negative trends.**

Upper East Columbia Monthly Yield	Monthly Temperature			Cumulative DD>18°C		
	Full Record	Pre 1980	Post 1980	Full Record	Pre 1980	Post 1980
January	0.25**	034**	-0.07			
February	0.19*	0.20	0.25			
March	0.25**	0.28**	0.35*			
April	0.64***	0.64***	0.67***			
May	0.63***	0.63***	0.68***			
June	0.30**	0.35**	0.18	-0.18	-0.02	-0.44**
July	-0.05	-0.09	0.03	-0.46***	-0.46***	-0.49**
August	0.29**	0.29**	0.44**	-0.40***	-0.37**	-0.49**
September	0.28**	0.38**	0.04	-0.25**	-0.24*	-0.33*
October	0.22**	0.0.3	0.38**	-0.17	-0.14	-0.21
November	0.21*	0.32**	0.05	-0.27**	-0.31**	-0.21
December	0.25**	0.17	0.41**	-0.22**	-0.26*	-0.12

Table 4.2.22 Correlation coefficients for the Upper West Columbia yields to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001. Bold highlights negative trends.**

Upper West Columbia Monthly Yield	Monthly Temperature			Cumulative DD>18°C		
	Full Record	Pre 1980	Post 1980	Full Record	Pre 1980	Post 1980
January	0.01	0.18	-0.08			
February	0.41***	0.50**	0.37**			
March	0.52***	0.34*	0.56***			
April	0.63***	0.49**	0.78***			
May	0.74***	0.78***	0.71***	0.07	0.29	-0.10
June	0.22*	0.31*	0.16	-0.38***	-0.14	-0.64***
July	-0.29**	-0.27	-0.32**	-0.52***	-0.56***	-0.49**
August	-0.04	-0.16	0.18	-0.54***	-0.46**	-0.62***
September	0.01	0.10	-0.13	-0.25***	-0.21	-0.35**
October	0.18	-0.10	0.31*	-0.03	0.06	-0.12
November	0.12	0.08	0.14	-0.21	-0.14	-0.32*
December	0.17	0.22	0.13	-0.22	-0.23	-0.21

Table 4.2.23 Correlation coefficients for the East Columbia yields to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001. Bold highlights negative trends.**

East Columbia Monthly Yield	Monthly Temperature			Cumulative DD>18°C		
	Full Record	Pre 1980	Post 1980	Full Record	Pre 1980	Post 1980
January	0.20	0.20	0.19			
February	0.13	0.09	0.21			
March	0.38***	0.37**	0.29			
April	0.53***	0.61***	0.42**			
May	0.04	0.15	-0.03	-0.04	-0.01	-0.07
June	-0.19*	-0.10	-0.31*	-0.47***	-0.53***	-0.39**
July	-0.36***	-0.30**	-0.45**	-0.39***	-0.40***	-0.38**
August	-0.13	-0.21	0.00	-0.45***	-0.38**	-0.57***
September	-0.31**	-0.28**	-0.35**	-0.18*	-0.09	-0.31*
October	-0.02	-0.09	0.14	-0.17	-0.11	-0.22
November	0.07	0.04	0.08	-0.11	-0.22	-0.05
December	0.14	0.17	0.05	-0.05	0.01	-0.09

Table 4.2.24 Correlation coefficients for the West Columbia yields to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001. Bold highlights negative trends.**

West Columbia Monthly Yield	Monthly Temperature			Cumulative DD>18°C		
	Full Record	Pre 1980	Post 1980	Full Record	Pre 1980	Post 1980
January	0.20*	0.33**	0.06			
February	0.22**	0.21	0.24			
March	0.58***	0.54***	0.59***			
April	0.77***	0.77***	0.75***			
May	0.66***	0.75***	0.53***	0.13	0.14	0.08
June	0.01	0.11	-0.09	-0.43***	-0.36**	-0.68***
July	-0.29**	-0.29**	-0.38**	-0.48***	-0.52***	-0.41**
August	-0.30**	-0.37**	0.04	-0.57***	-0.58***	-0.62***
September	-0.38***	-0.36**	-0.52***	-0.32***	-0.33**	-0.28
October	0.03	-0.09	0.24	-0.17	-0.15	-0.17
November	0.25**	0.39**	0.13	-0.23**	-0.22	-0.25
December	0.16	0.29**	-0.04	-0.22**	-0.22	-0.19

Table 4.2.25 Correlation coefficients for the Lower Columbia yields to temperature metrics. Stars indicate significance at * *p*<0.01,*p*<0.0.5, *** *p*<0.001. Bold highlights negative trends.**

Lower Columbia Monthly Yield	Monthly Temperature			Cumulative DD>18°C		
	Full Record	Pre 1980	Post 1980	Full Record	Pre 1980	Post 1980
January	0.14	0.07	0.17			
February	0.28**	0.21	0.33*			
March	0.53***	0.42***	0.49**			
April	0.62***	0.62***	0.63***			
May	0.28**	0.41***	0.07	-0.32***	-0.31**	-0.37**
June	-0.10	0.03	-0.34**	-0.54***	-0.54***	-0.54***
July	-0.46***	-0.41***	-0.51***	-0.32***	-0.34**	-0.29
August	-0.26**	-0.41***	-0.03	-0.48***	-0.44***	-0.61***
September	-0.36***	-0.37**	-0.38**	-0.25**	-0.25*	-0.31*
October	-0.03	-0.07	0.06	-0.20*	-0.20	-0.22
November	0.23	0.28**	0.16	-0.26***	-0.29**	-0.23
December	0.12	0.17	0.06	-0.15	-0.17	-0..09

Comparison of time series to mechanistic model projections

We compare measured stream data at locations where hydrologic model output is available. These include, the Pacific Climate Impacts Consortium Bias Correction and Spatial Disaggregation (PCIC BCSD), University of Washington Bias Correction and Spatial Disaggregation (UW BCSC), and the University of Washington Hybrid Delta (UWHD) (Hamlet et al. 2013b). In the Mica Basin, the annual yield is currently 7-17% lower than the line of prediction based on the above scenarios (Figure 4.2.49). Further, the models all predict a trend that is increasing, while the actual data indicates a declining trend. Dividing the results seasonally, it appears that the models are over-predicting in both the cool (October to March) and warm season (April to September), and August flow (Figure 4.2.50-4.2.52). In the Kootenay River above the Corra Linn dam the annual yield is currently 8-14% lower than the line of prediction based on the above scenarios (Figure 4.2.53). In the Kootenay, cool season flow is at present over predicted significantly (+15 to +67% projected increase) as current trends show strong declines through the last 30 years (Figure 4.2.54). The current trend is on par with the projected warm season flow at +1 to +9% projected increase (Figure 4.2.55). Annual yield in the Duncan River is currently 5-10% lower than the line of prediction (Figure 4.2.57). Based on present trends, cool season flow is over-predicted by only two of the models, the UW HD at +11% projected increase, and the PCIC BCSD at +13% projected increase, but on par with the UW BCSD at +2% projected increase (Figure 4.2.58). Warm season flow is over predicted in all the models (Figure 4.2.59). The measured yield of the Columbia at Birchbank is at present 5 to 10% lower than the lines of projection that estimate an increase in yield by +5 to +15% for the 2030-2059 time period (Figure 4.2.61). The latter cannot be divided seasonally because flow is regulated throughout the year.

Mica Basin

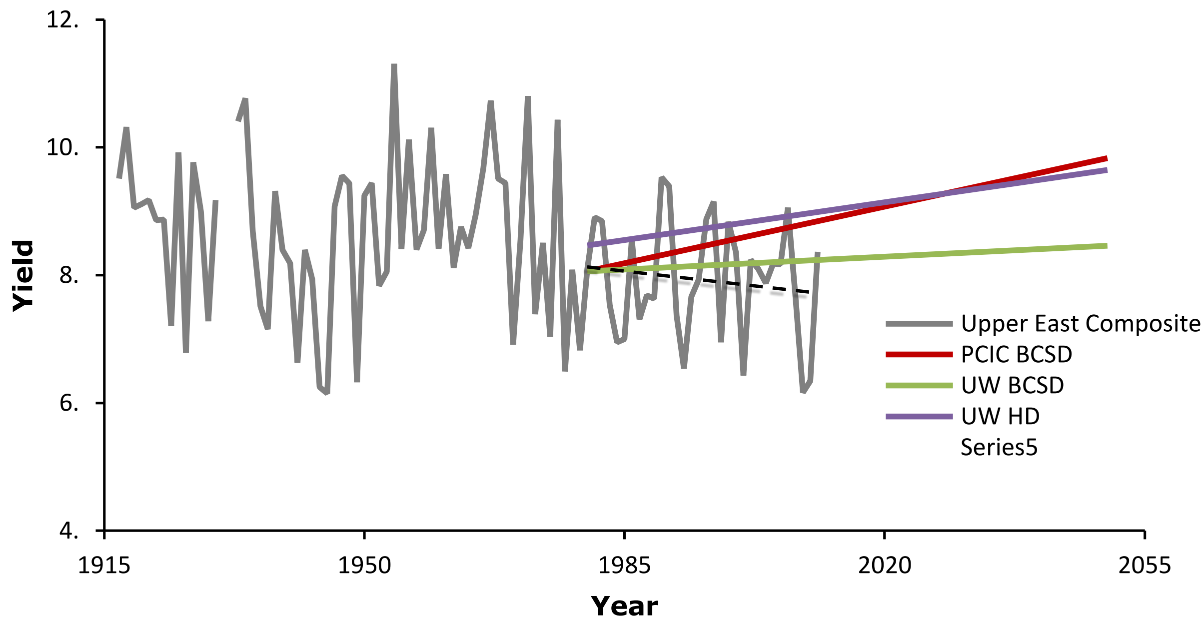


Figure 4.2.49 Comparison of measured annual yield data in the Mica basin alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +5 to +22% increase in annual streamflow. The dashed line represents the trend line from 1980 to 2011.

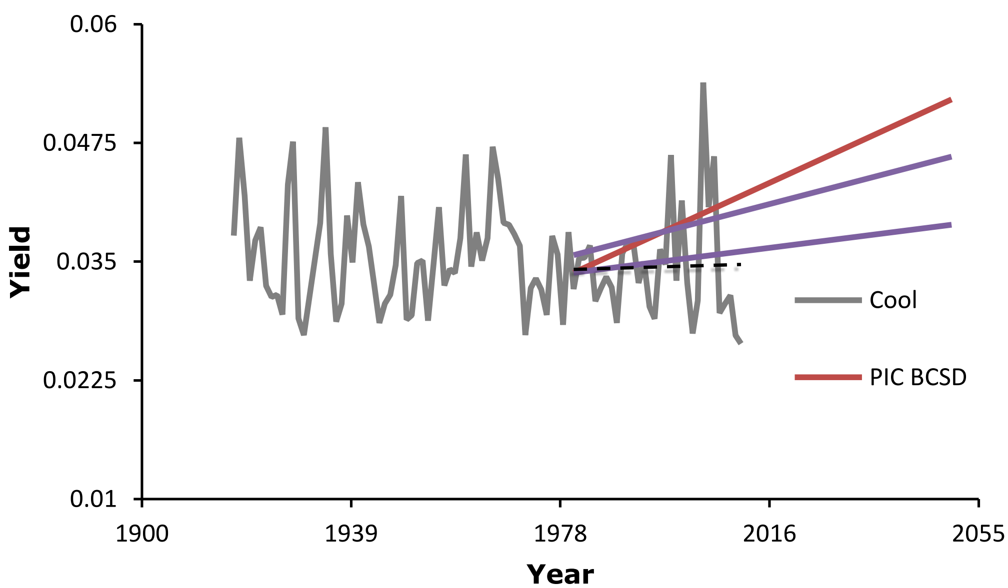


Figure 4.2.50 Comparison of measured Cool season (October to March) data in the Mica basin alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +15 `to +54% increase in cool season streamflow. The dashed line represents the trend line from 1980 to 2011.

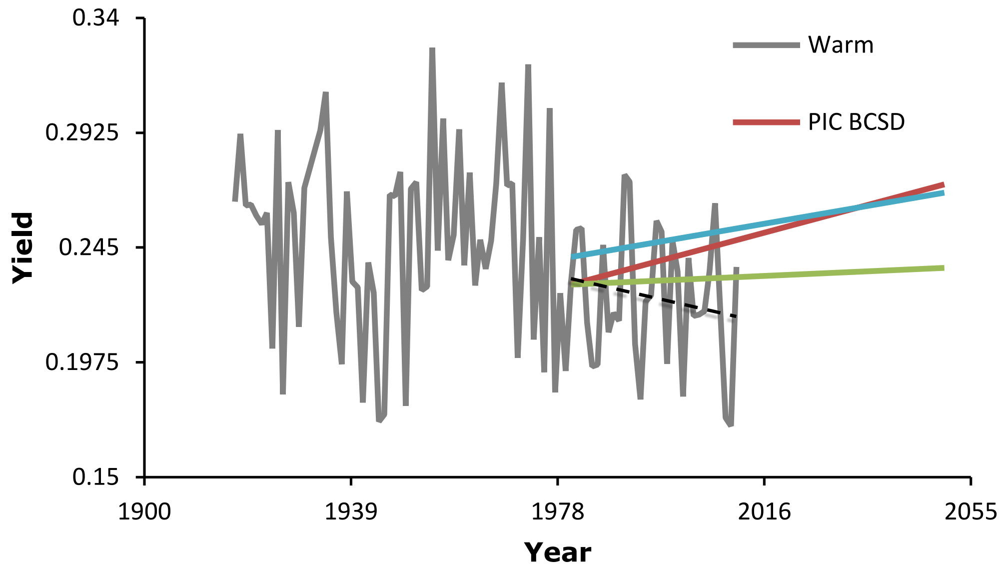


Figure 4.2.51 Comparison of measured Warm season (April to September) data in the Mica basin alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +3 to +18% increase in warm season streamflow. The dashed line represents the trend line from 1980 to 2011.

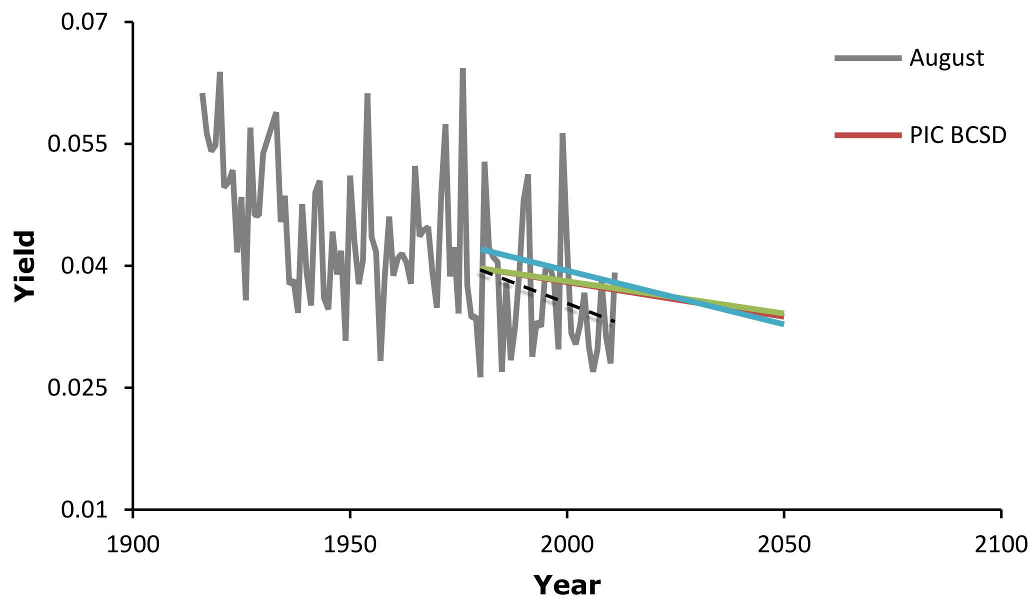


Figure 4.2.52 Comparison of measured August yield data in the Mica basin alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a -14 to -22% decrease in August streamflow. The dashed line represents the trend line from 1980 to 2011.

Kootenay River above Corra Linn

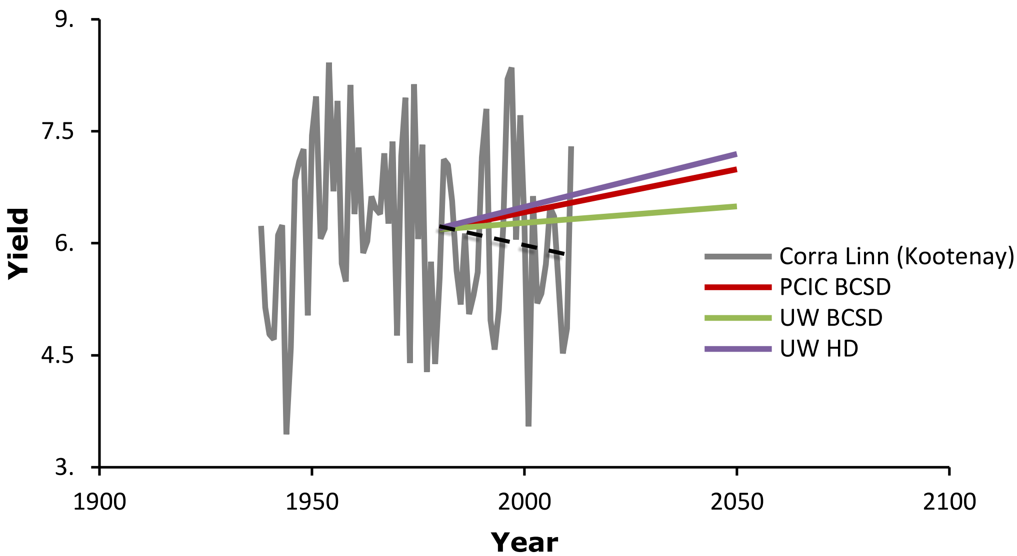


Figure 4.2.53 Comparison of measured annual yield data in the Kootenay River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +5 to +16% increase in annual streamflow. The dashed line represents the trend line from 1980 to 2011.

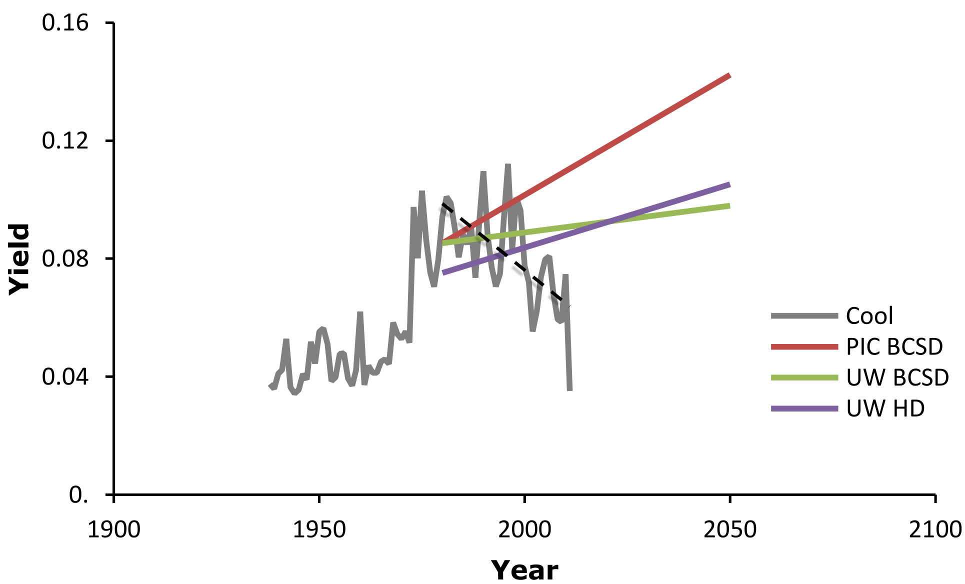


Figure 4.2.54 Comparison of measured Cool season (October to March) data in the Kootenay River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +15 to +67% increase in cool season streamflow. The dashed line represents the trend line from 1980 to 2011.

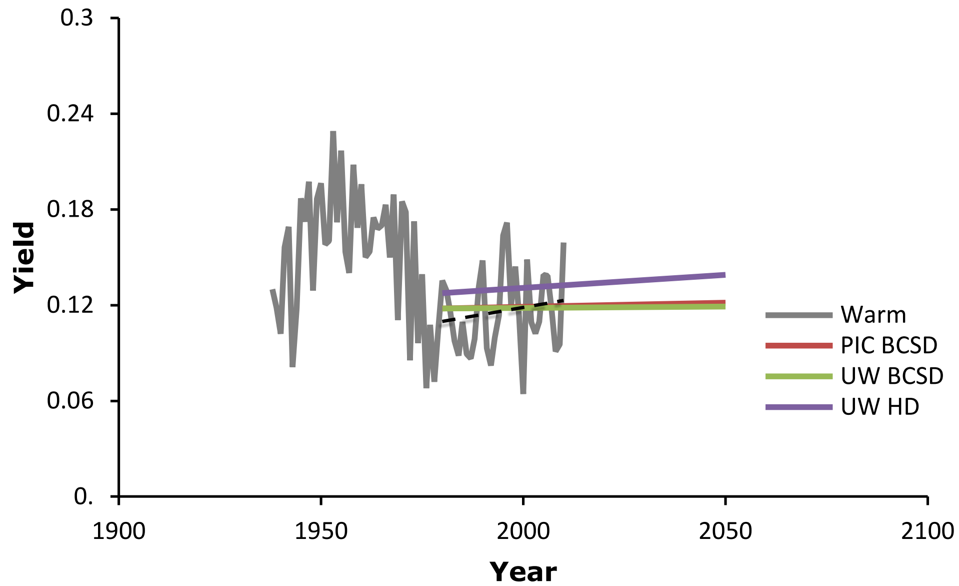


Figure 4.2.55 Comparison of measured Warm season (April to September) data in the Kootenay River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +1 to +9% increase in warm season streamflow. The dashed line represents the trend line from 1980 to 2011.

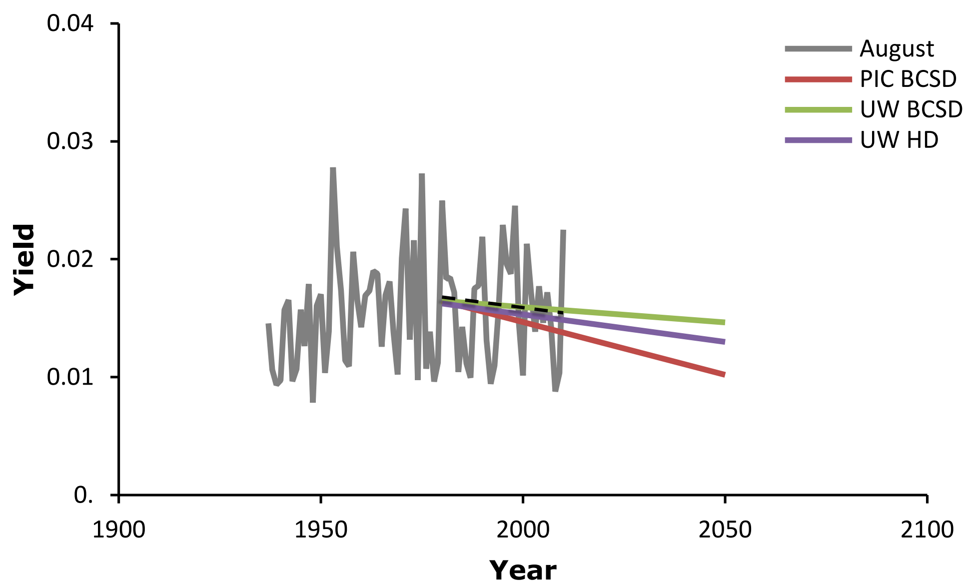


Figure 4.2.56. Comparison of measured August yield data in the Kootenay River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a -11 to -38% decrease in August streamflow. The dashed line represents the trend line from 1980 to 2011.

Duncan River

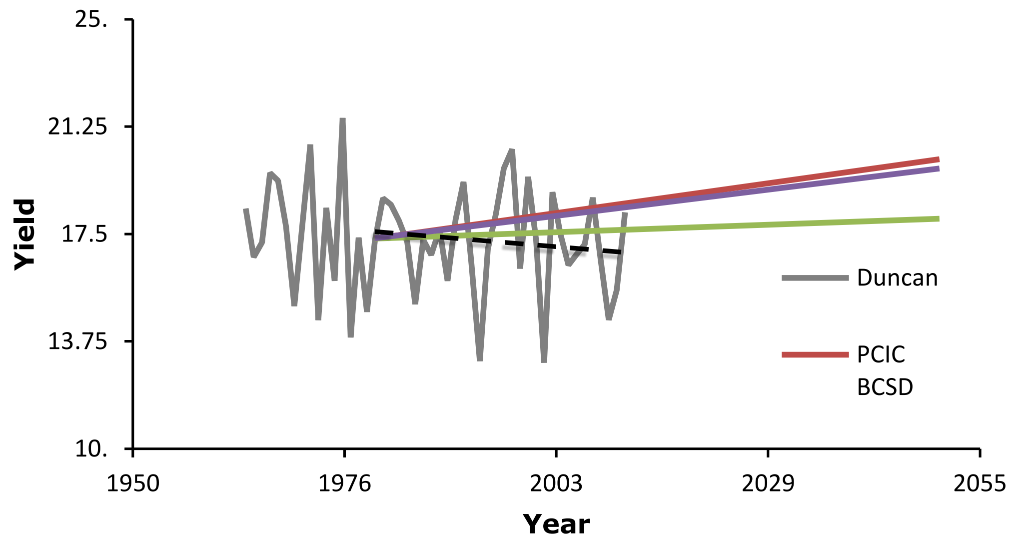


Figure 4.2.57 Comparison of measured annual yield data in the Duncan River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +4 to +16% increase in annual streamflow. The dashed line represents the trend line from 1980 to 2011.

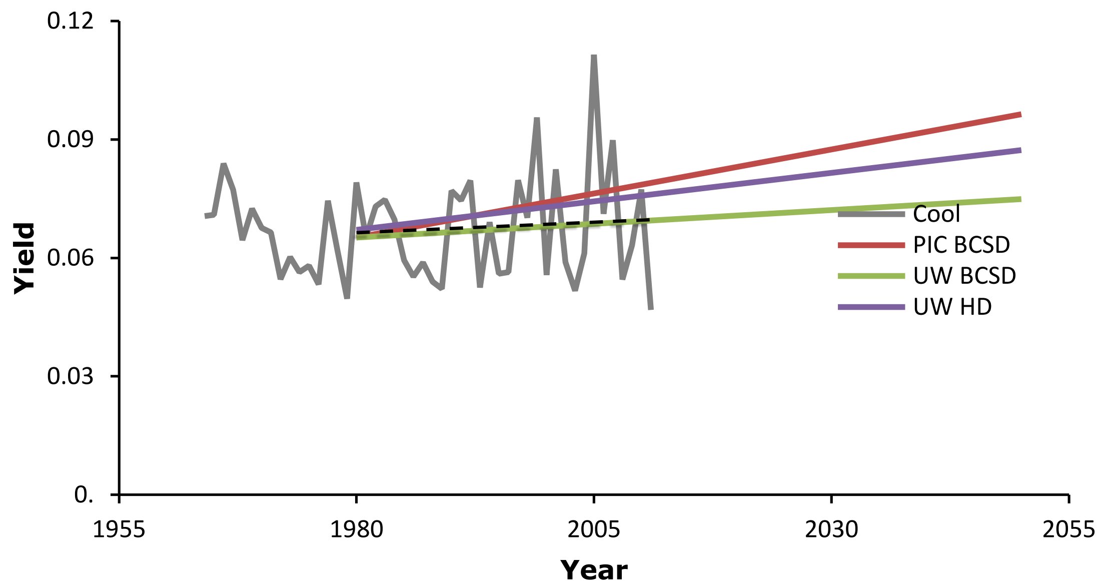


Figure 4.2.58 Comparison of measured Cool season (October to March) data in the Duncan River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +15 to +48% increase in cool season streamflow. The dashed line represents the trend line from 1980 to 2011.

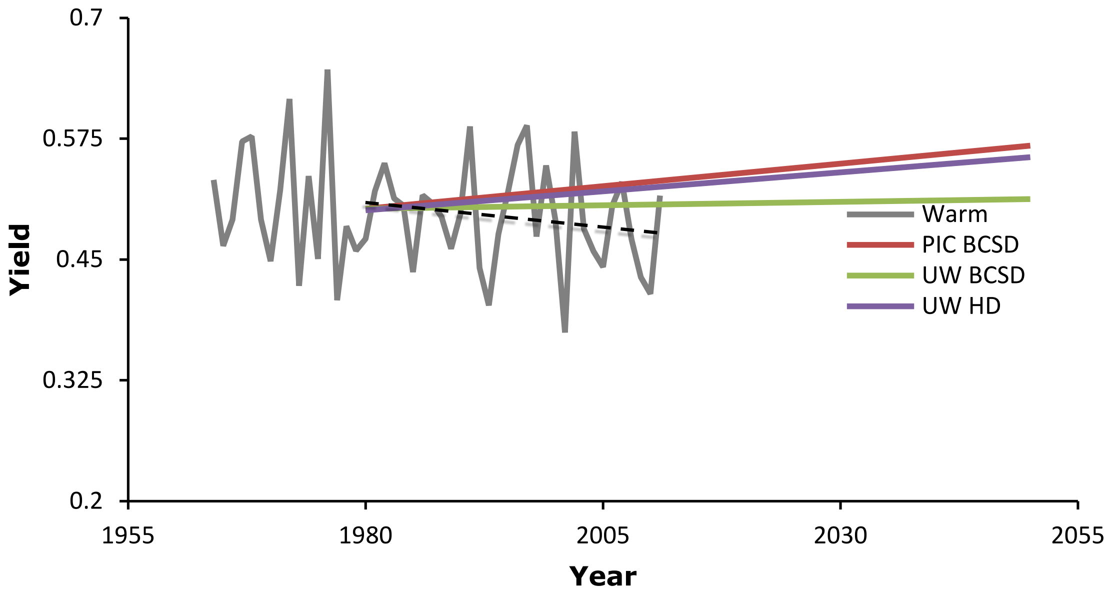


Figure 4.2.59 Comparison of measured Warm season (April to September) data in the Duncan River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +2 to +13% increase in warm season streamflow. The dashed line represents the trend line from 1980 to 2011.

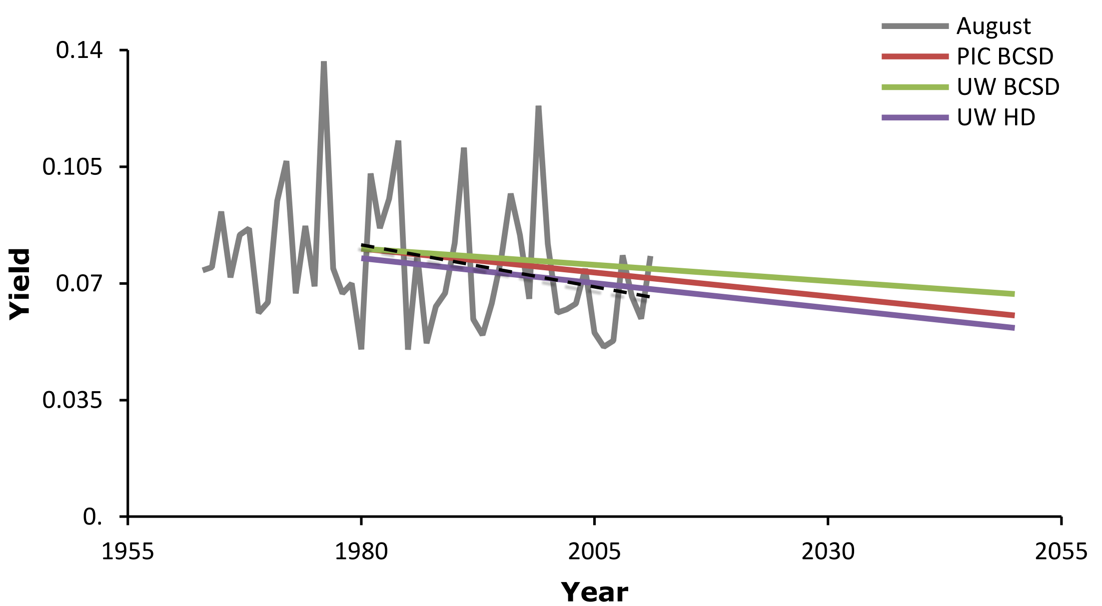


Figure 4.2.60. Comparison of measured August yield data in the Duncan River alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a -17 to -27% decrease in August streamflow. The dashed line represents the trend line from 1980 to 2011.

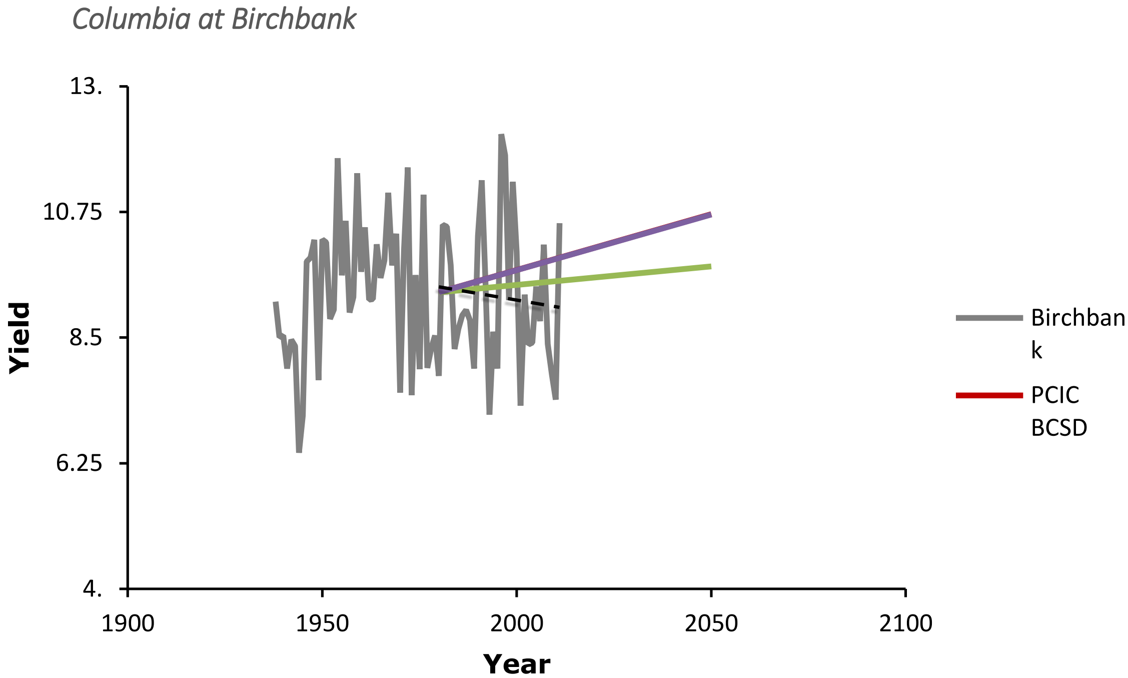


Figure 4.2.61 Comparison of measured annual yield data in the Columbia River at Birchbank alongside three projections of annual changes from the 1970-1999 baseline to the 2030-2050 time period for the A1B scenario. The models predict a +5 to +15% increase in annual streamflow. The dashed line represents the trend line from 1980 to 2011.

Discussion

The statistical separation of the stream data into five regions allows the composite time-series to provide a regional perspective on the historical and potential future changes in stream yield. Because the streams analyzed within each region were highly correlated to each composite time series, it is likely that unmonitored streams in the respective regions have undergone similar changes and have similar relationships to climate variables. Exceptions include two highly glaciated streams in the Upper East Columbia region, Beaver and Canoe Creeks. These two creeks exhibit different trends, and different relationships to all climate indices and temperature metrics. These differences highlight the lack of representation from the upper areas of the CBTR presenting a significant data and knowledge gap.

As with the climate data, we found strong historical relationships to the PDO, ENSO, and NOI, though there is some evidence that these relationship may be changing. The time series show strong negative relationships to the PDO and ENSO, and strong positive relationship to the NOI. However, in the last ten to fifteen years there has been an increase in years with a negative PDO and ENSO, as well as a positive NOI (Figures A1-A3); historically this would predict an increase in yield through this time period. At present, there is no evidence for an increase in yield (Figures 4.2.14-4.2.38), and removing the effects of the Pacific climate indices results in strong negative trends (Figures 4.2.39-4.2.43). These observations are suggestive of a regime shift in the relationship between Pacific climate indices and hydrometric variables in the CBTR, and warrant further study.

In other regions of the Pacific Northwest and the Rocky mountains, the effects of Pacific climate indices have also changed. Pederson et al. (2013) report that prior to 1980, a north-south dipole existed between the southern and northern Rocky mountain spring snow water equivalent related to Pacific climate modes; however, since 1980 there have been persistent and synchronous declines in snowpack driven primarily by increases in spring temperatures. (See also Mote et al. 2005; Mote 2006; Pierce et al. 2008). These changes have resulted in an earlier runoff and peak flow through much of the US Rocky Mountains. Though in the CBTR there have not been significant shifts in the timing of flow, there are strong negative relationships between temperature intensity and stream yield, and the strength of this relationship is greater post 1980 (Table 4.2.20-4.2.24). In addition, annual and monthly yield correlations to the PDO, ENSO, and NOI have changed pre- and post-1980 (data not shown). Taken together these observations suggest that regional climate warming is overprinting the effects of natural variability (Pacific climate indices) on stream yield. It is worth noting, that an additional component not accounted for in this analysis is the area logged or impacted by beetle kill or fire. Generally, the loss of vegetation in the catchment results in an increase in catchment yield. However, large areas of logged terrain can expose snow to more solar radiation in the winter, leading to increased sublimation (Winkler et al. 2010; Molotch et al. 2009). Evaluating this hypothesis is beyond the scope of this report; however, it highlights that there any many unanswered questions pertaining to the cause of stream yield changes in the Columbia Basin of Canada.

Comparing the stream data to model results reveals discrepancies between projected flow and the current trajectory. The differences occur in the cool season flow, and in the warm season flow of glaciated basins. This is possibly due to treatment of water resources at high elevations by the models. The lack of calibration and validation data at these altitudes leads to the uncertainty in model parameters.

The onset of freshet and the date of center volume are two metrics typically used to evaluate the effects of a changing climate on stream hydrology. These are used in the State of the Basin Report for the Canadian Columbia Basin. However, in the Columbia Basin changes in these variables are minor and non-significant despite notable climate related effects on stream hydrographs and annual yield. We therefore recommend as an alternative using peak yield and/or the late summer yield as measures of change.

4.2.2 Summary of Data and Knowledge Gaps

There are several critical data and knowledge gaps with respect to streamflow and streamflow characteristics in the CBTR that can lead to limitations in water resource planning.

- Inadequate representation of hydrometric stream data in the upper 120 km of the CBTR. This region is the heaviest glaciated area and therefore has important implications for managing flow through the ongoing and future climate changes
- Inadequate representation of stream hydrometric data for watersheds below 50 km^2
- Inadequate hydrometric station density: the WMO recommends an minimum of one station per 1000 km^2 area, ideally one station per 300 km^2 area.
- Though there has been an apparent increase in precipitation (Section 3), and downscaled climate models and corresponding hydrologic models predict increase in precipitation and runoff with increasing temperatures, neither an increase in peak yield nor an increase in annual yield has manifested highlighting our limited understanding of the various controls on streamflow in the basin
- There are strong negative relationships to temperature intensity that increase through successive time periods. This suggests that the relationship between temperature intensity and evaporation changes when the number of days with temperatures above 18^0C increases in number and frequency. There are presently many unanswered questions surrounding these effects of increases in temperature intensity and water yield in the CBTR
- There are no paired watershed studies in the basin to evaluate landscape effects on regional hydrologic resources
- There is no online resource for end-users (Forestry, Transportation, Mining, Water Supply, Agriculture, etc.) to evaluate hydrometrics in unmonitored streams. Previous work from the Ministry of Sustainable Resource Management (Obedkof 2002) is based on a limited dataset and needs to be updated
- Data accessibility; there is a large amount of data being collected by organization and consulting firms that are not a part of the integrated network available through the Water Survey of Canada
- Data accessibility; though there is at least one watershed within the CBTR where extensive research has been done through FLNRO, data is not publicly available.
- There are only 22 streams monitored for water quality, most are high order streams and within watersheds greater than 500 km^2
- Monitoring for water quality directed towards point sources not diffuse sources
- There is a lack of reference sites across elevation and stream orders for both water quality and quantity
- Updates are needed for the reference condition models in the CBTR

- Updates are needed for the water quality objectives
- There are no paired watershed studies in the basin to evaluate land-use and or regional effects on water quality
- Pharmaceuticals, pesticides, and other organic contaminants are known issues and are not measured or monitored
- Cumulative effects analyses on streams are not widely conducted
- There are problems with data accessibility

4.2.3 Recommendations

Various factors will contribute to the amount of hydrometric and water quality related data in any given region, including population density, data collection objectives, financial support, and access to remote and difficult terrain. However, there are considerable financial, social, and economic implications of not having enough data, particularly in the CBTR where water resources are of paramount importance. The former BC Ministry of Sustainable Resource Management published a Business Review of the BC Hydrometric Program (Azar et al. 2003), which discusses the need for hydrometric data by sector and performs a cost benefit analyses of the value of hydrometric data. Sectors that would benefit from the network include:

- Forestry
- Transportation (Road and Rail)
- Hydropower
- Mining
- Agriculture
- Oil and Gas
- Sewage Treatment
- Water Supply
- Flood Mitigation
- Resource Management
- Government Programs

Though acknowledged and not strictly a part of the Business review, the academic and research communities both locally and internationally benefit from the availability of hydrometric and water quality data.

The review highlights how many of the end-user organizations underestimate the value and benefits that occur from these data, and for those that do, the dispersed nature of the end-users makes it difficult to voice support for the program. Importantly, the program is apparently only capturing a fraction of the potential in part due to a lack of leadership as well as program shortcomings.

To address the needs of the end-users, we recommend:

1) Support the establishment of research networks that include federal and provincial monitoring agencies, stakeholders, and researchers to identify the needs for hydrometric data, and different domains of hydrometric information as they relate to various organizations' mandates and activities.

2) Support monitoring programs and research that will 1) provide a greater understanding on how streamflow in the CBTR responds to ongoing land-use and climatic changes and 2) add to the hydrometric network with respect to both stations numbers and coverage as well as technology. Specific projects and tasks may include:

    a. Support research and data collection activities that investigate the temperature and synergistic effects with land-use on evapotranspiration and yield in the CBTR.

    b. Support hydrologic model analyses that include the effects of climate and land-use change in the basin.

    c. Support stream data hydrometric collection in the CBTR for 1) upper reaches of the CBTR, 2) higher elevations in the basin, paired stream and paired catchments, 3) paired with glacier monitoring programs, and 4) in watersheds area categories that are poorly represented (specifically <50 km^2).

    d. Support research and investigations on climate related effects in water resources in small watersheds with elevated sensitivity to change. This is critical in dryer areas where the water use and planning is required to maintain environmental flow as described in the Water Sustainability Act.

    e. Support the establishment of pilot watersheds in each statistical region to assist with low flow monitoring, watershed management, water stewardship, and drought management.

    f. Support research to understand and evaluate the effects of increased evaporation on lakes, stream, and snowpack as well as any interaction with changing melt regimes (e.g. isotope analyses).

2) Collaborate with UBCO and SGRC to provide operational hydrometric documents for use by all end-user sectors including online graphs and applied models for determining hydrometric variables in unmonitored streams (annual flow, monthly flow, peak flow, minimum flow, flood recurrence intervals). Ideally the data could be incorporated into a PRISM type mapping system where users could obtain the necessary information by clicking on a watershed.

3) The above analyses highlight significant knowledge gaps with respect to future streamflow volumes and their relationship to Pacific Climate Indices and climate change. We therefore recommend evaluating regime shifts for regionalized streamflow hydrometrics as well as the relationship of the Pacific Climate Indices to hydrometrics at least every 5 years.

4) We recommend that the State of the Basin report produced by Columbia Basin Rural Development Institute add indicators that better represent climate related hydrometric changes

in the CBTR, specifically peak flow and late summer yield. Monitoring the onset of freshet should continue, though centre volume does not appear to change appreciably in CBTR despite significant climate change and this metric has been shown to be ineffective in representing changing flow regimes (Déry et al. 2009).

5) Avoid further reductions to the hydrometric and water quality network of BC.

6) Integrate data collected by various agencies in the CBTR. All should be reported along with flags that indicate quality parameters and should be housed on a central registry maintained by government.

7) Investigate opportunities to enhance the existing network through local citizen science groups, businesses, and/or collaborations with research groups and government authorities.

    a. Educate local communities on the socio-economic importance of hydrometric monitoring and provide resources for the establishment of stream gauges and maintenance. This is potentially critical for groups like CABIN, where stream chemistry data is collected but volumetric data is often not available, which considerably diminishes the value of the data.

    b. Collaborate with research groups and universities to create opportunities for network growth. Once a station is established through research protocol, federal/provincial agencies may opt to provide maintenance support. For example, the establishment of the Parks Illecillewaet mass balance monitoring station was initiated through a short-term research project.

8) Assist provincial government with the identification and risk rating of drought, flood and debris flow hazards associated with changes in climate and hydrometrics. Enhance monitoring in these regions.

9) Assist provincial government with the identification of water bodies with current or expected quality concerns.

10) Support the training and maintenance of expertise in citizen science groups.

11) Support an expansion of the cumulative effects model for watersheds of concern.

12) Support greater access of CABIN data and other data online.

13) Due to the large natural variability of these systems, probability tools should be developed for stream health indicators. This will avoid the assignment of a bad status to a particular water body for unnecessary reasons.

14) Recommended Hydrometric Indicators:

    We recommend a list of streamwater quantity indicators that can be used by various community groups and different levels of government to better understand the changing state of water availability in the CBTR. The onset of freshet and the date of centre volume are used in the State of the Basin report to evaluate climate related changes in stream hydrology. However, despite notable and significant changes in hydrology through the CBT region, these variables have not changed appreciably**.** We therefore, in addition to current metrics, recommend evaluating:

- Changes in annual peak yield
- Changes in the late summer minimum yield
- Changes in streamflow variability at monthly time scales

Changes in precipitation type and amount will have considerable impact on the timing and volume of flow in any given year. With increased temperatures, a shift to more precipitation falling as rain in the winter is expected, as well a reduced spring snowpack. We therefore recommend evaluating:

- Annual rain: snow ratio
- Spring snow water equivalent
- Winter snowfall as well as October through December precipitation. They are both strong determinants of stream yield in the following year, accounting for 27-35% of the variability (Section 5).
- Determine if the variability in precipitation is increasing during the wettest and driest months of the year.
- We further recommend the use of the regime shift indicator test (RSI) instead of trend analyses or arbitrary time period comparison due to the cyclic nature of many of the variables of interest.

5.0 Cryosphere: Snowpack, Glaciers, and Permafrost

5.1 Data Availability and Coverage

There are 49 snow pillow stations in the CBTR, 40 manual stations and 9 automated stations (Figure 5.1.1). The automated stations have associated climate data including temperature, cumulative precipitation and snow water equivalent. Data from manual stations are taken on the first of the month (or near to it) and include snow depth and snow water equivalent.

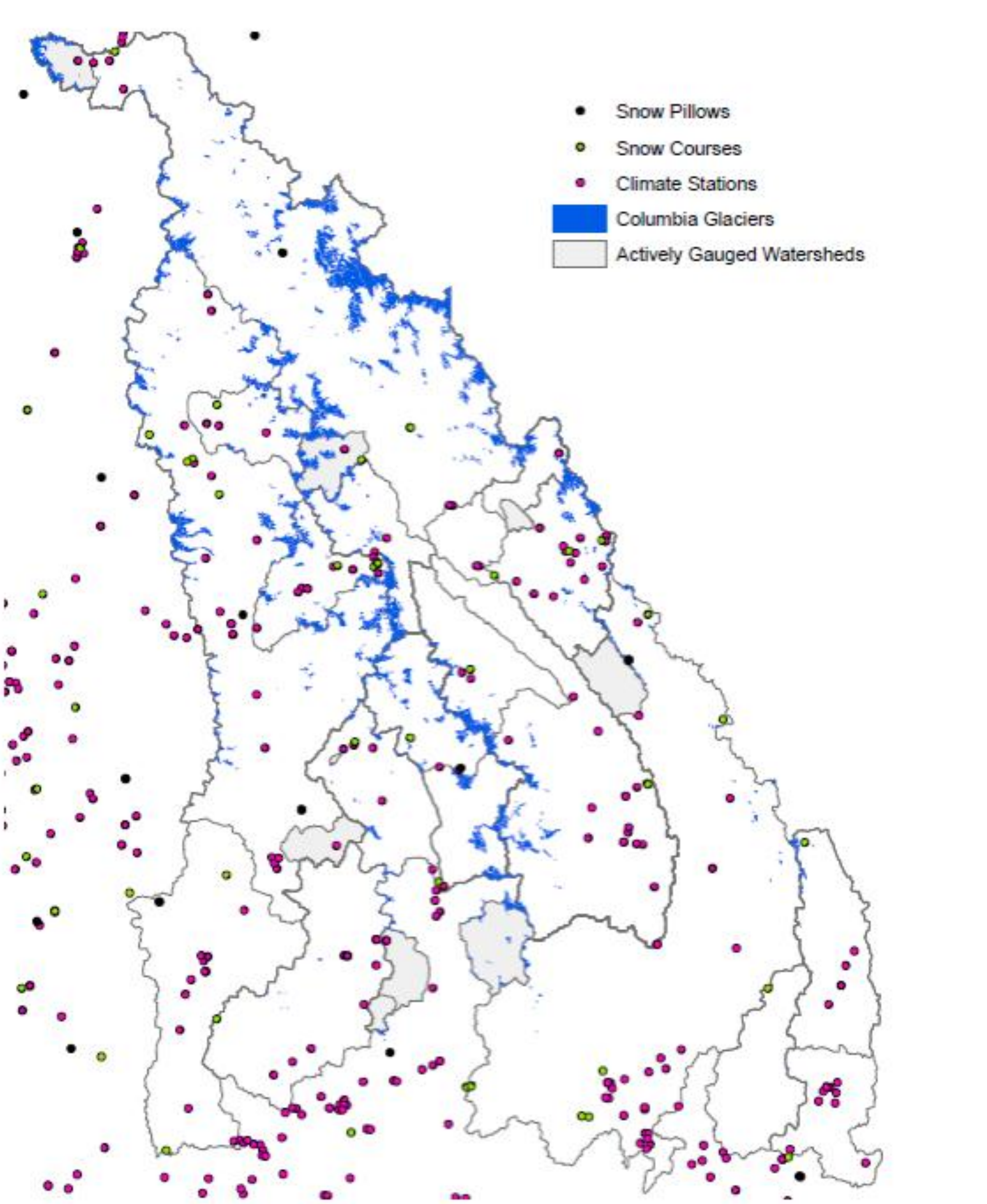


Figure 5.1.1 Reproduced from Trubilowicz, Moore, and Anslow (2010) . Glacier extent associated with Environment Canada Stream gauging stations.

Though the number of stations is compliant with WMO recommendations (WMO 1981)(Table 5.1.1), there is an insufficient number of stations above 2000 m for hydrologic modelling and to adequately assess recent climate changes to the snowpack (CBT, Cryosphere Research Network)(Table 5.1.2, 5.1.3). There are 43 snow pillow stations with more than 30 years of data, and 19 stations with more than 50 years of data.

Table 5.1.1 Percent station coverage for each region based on WMO guidelines. Ideal coverage is one station per 2000 km^2, and the minimum coverage is one station per 3000 km^2.

	Upper East	Upper West	East	West	Lower
% of Ideal	119%	155%	90%	135%	141%
% of Minimum	178%	232%	134%	202%	211%

Table 5.1.2 Automated snow pillow station by region and altitude

Automated Snow Pillow	Upper East	Upper West	East	West	Lower	Total
<1000 masl						0
1000-2000 masl	1	2	2	1		6
>2000 masl	1	1		1		3
Total	2	3	2	2	0	**9**

Table 5.1.3 Manual snow pillow station by region and altitude

Manual Snow Pillow	Upper East	Upper West	East	West	Lower	Total
<1000 masl	1	2		1	1	5
1000-2000 masl	9	7	4	4	5	29
>2000 masl	4		2			6
Total	14	9	6	5	6	**40**

The lack of long-term mass balance data for glaciers in the CBTR is a considerable knowledge gap. To address this gap, mass-balance measurements are presently being taken on 5 glaciers including Wapta and Illecillewaet glaciers (Parks Canada), Bryce in the Columbia Icefields (Demuth, GSC), and Zilmer and Kokanee glaciers (Menounos et al., UNBC). A glacier inventory for the CBT and BC Hydro was performed in 2010 by Trubilowicz, Moore, and Anslow; it, however, does not appear to be available online. The thinning and retreat of glaciers will not only affect streamflow volume but (also) produce geomorphic hazards including slope failures and outburst floods (Moore et al. 2009).

The author could not find any information on permafrost extent in the CBTR and there are no federal sites being monitored within the region. Since melting of permafrost in mountain environments can affect slope stability (Geertsema et al. 2006), ecosystem health, and water quality, (Frey and McClelland 2009) this is a considerable data and knowledge gap.

CBT Cryosphere Research Group

In December 2013, the CBT organized a meeting of the Cryosphere Research Group, which included a wide variety of interested parties and stakeholders including Ministry of Environment, BC Hydro, Canadian Avalanche Association, Environment Canada, Natural Resources Canada, Parks Canada, Pacific Climate Impacts Consortium, Selkirk College, University of Northern British Columbia, University of British Columbia (Vancouver and Okanagan), and University of Innsbruck and Alp-S representatives. The workshop was geared towards networking amongst data end-users with an aim to identify current activities, data collection priorities, establish partnerships, and determine the resources needed to fill the identified data and knowledge gaps. Several key research questions were identified:

- How have elevation gradients and spatial variability of winter precipitation & snowpack changed?
- What is the spatial distribution of high elevation SWE?
- How have historic and future changes in our glaciers affected stream flow characteristics at multiple scales?
- What are the trends in glacier mass balance across gradients?
- How can we scale up from local monitoring to regional scale glacier behaviour?
- Can a “life expectancy” analysis be applied to the Basin’s glaciers? (see Parks Canada State of Park reports)
- What is the impact of extreme temperature and precipitation events on glaciers?
- What is the role of glaciers in moderating or exacerbating impacts of extreme events?
- What is the lag time between climate events and glacier response?
- Where are Basin glaciers in relation to peak runoff?
- What can we learn from the 2003 heat wave in the Alps in regards to glacier science, increasing public communications/awareness and water resource use/planning?

As well as key data questions:

- How can crowdsourcing/citizen science be used to improve our understanding of the cryosphere?
- What is the best approach to synthesize and display point and aerial observations of snow for daily to seasonal forecasts?

- What is the best data storage and delivery mechanism and who can lead it? (consider both internal and external delivery, including public communication tools)
- How can measurement approaches for snow depth, SWE & density be standardized?

The meeting was a success and has led to important untapped data discoveries, namely the INFOEX database maintained by the Canadian Avalanche Association. The database is subscriber based and a sub-committee was formed to work on accessibility issues. The workshop also led to the identification of ideal 'Supersite' monitoring locations where glacier, hydrometrics, snow pillow, and climate data should be paired. Environment Canada is amenable to adding hydrometric stations to the existing network provided adequate funds are available. The network created several documents with outlining ideas for expanding the monitoring network, technology upgrades, data sharing, and research objectives.

5.2 Data Analyses

Introduction

The flow regime in the Columbia Basin Trust Region (CBTR) is dominated by melting of the annual snowpack in late spring and early summer. The annual snowpack represents a significant amount of water storage through the year, and can be volumetrically larger than reservoir capacities in the CBTR (Jost 2013). Glacier resources make up 2.6% of the CBTR (as of 2008) and range from 0-5% in the statistical hydrologic regions (Figure 5.2.1). Glacier resources represent long-term storage of water in the basin; though the volume of water stored in glaciers is smaller than the annual snowpack, their runoff contributions are important for both maintaining flow in the later summer and for water quality (Moore et al. 2009). Glacier contributions to August and September flow in the Mica basin are as high as 25 and 35% respectively (Jost et al. 2012), and 25% in the Illecillewaet river (Hirose and Marshall 2013). Because glaciers contribute significantly to late summer flow, their contributions are particularly important during warm dry summers with low winter snowfall accumulation.

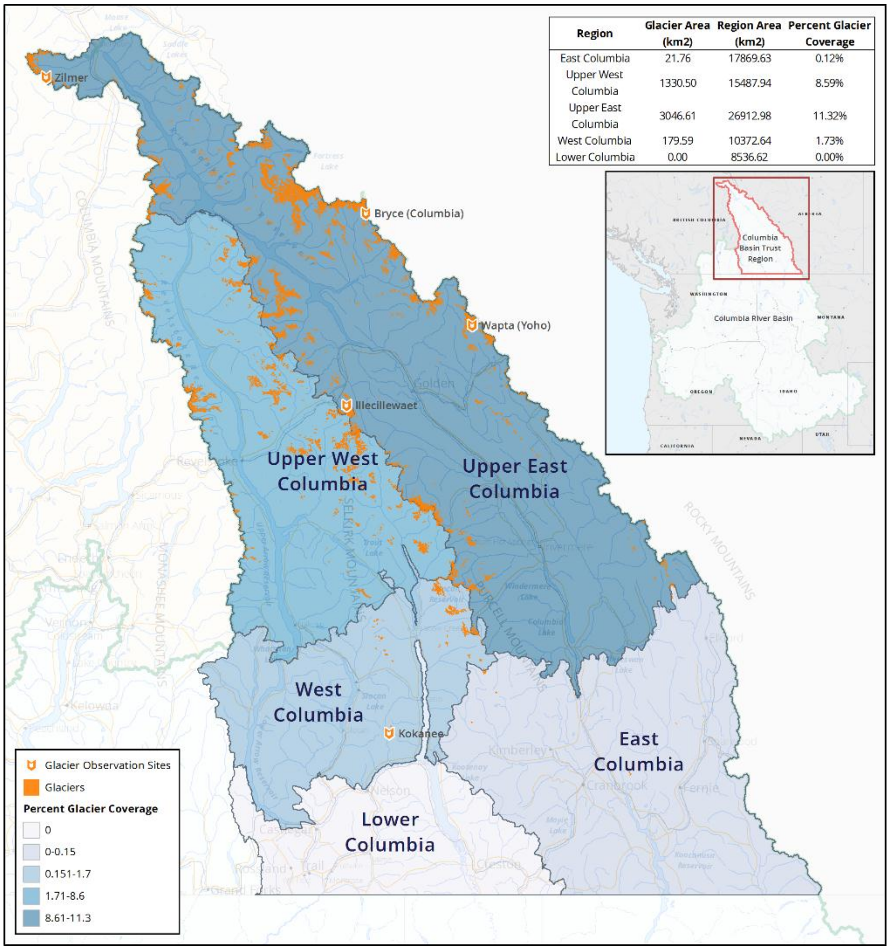


Figure 5.2.1 The Columbia Basin Trust Region (CBTR) showing glacier area and percent area by statistical hydrologic region.

The hydrologic regime of the Columbia Basin is sensitive to changes in climate, specifically regional temperature and the seasonal distribution of precipitation type and amount. In the last century temperatures increased by 1.6 ^{0}C in the southern regions of the CBTR, and by 1.1 ^{0}C in the northern regions (Section 3). In the coming years, temperature increases are expected to accelerate and increase by 1.1-4.8 ^{0}C by 2080 (IPCC 2013). Warmer temperatures means less precipitation falls as snow and glacier areas will decline; consequently, contributions from seasonal snowpack and glaciers will diminish.

Since the 1950s the Columbia and Kootenay regions have respectively seen a 20% and 24% reduction in snowpack. The majority of this decline, however, is due to shifts in Pacific Ocean climate indices. After removing the effects of the PDO and ENSO, the decline in snowpack is reduced to 5% and 6% respectively (Jost 2013). Glacier area has also declined through this period, a study compiling Landsat imagery found that glaciers in the CBTR have been retreating in the last few decades, with a ~15% reduction in glacier area (Bolch et al. 2010).

Glacier volume is sensitive to shifts in climate and warming and can cause a shift upwards of the equilibrium line altitude (ELA) causing glacier retreat. The ELA is the theoretical elevation where the net mass balance is zero, representing the transition from the upper reaches of the glacier where snow is

accumulating faster than it is ablating (melting and sublimating) to the lower reaches where the glacier is ablating faster than snow is accumulating. The mass-balance of a glacier, the difference between accumulation and ablation, determines whether or not a glacier advances or retreats. The initial response to a shift from a positive or neutral mass-balance to a negative mass-balance is an increase in meltwater production. However, if the conditions that favour a negative mass-balance persist, meltwater production will decrease as the glacier area diminishes. Late summer flows are among the lowest in the headwater streams of the Columbia, and are declining in most regions (Section 5). Therefore, determining whether or not glacier contributions to flow in the Columbia have peaked is critical for understanding and modelling the future streamflow response to climate warming.

Because long term mass-balance data does not exist for glaciers within the Columbia, it is unclear to what extent glacier contributions to flow have changed alongside the climate and therefore how they may respond in the future. This omission represents a critical information gap for hydrologic models used in the region, causing considerable uncertainty in future projections of streamflow from these glaciated basins (Schnorbus et al. 2012). To address this issue, several recent medium to long-term mass-balance studies have been recently established; these include the Yapta and Bryce glaciers in the Columbia Icefields, and Zilmer and Kokanee glacier ((Figure 5.2.1). These glaciers are spread through the CBTR to provide a spatial understanding of glacier responses to current climate, and the data collected will be used to calibrate the glacier and mass-balance models used in the regions.

Research evaluating glacier contributions to flow in the CBTR has yielded some apparent conflicting results. Stahl and Moore (2006) used climate corrected August streamflow trends from glaciated basins to determine that glacial contributions to streamflow were declining in this region. They found dominantly negative trends through the 1976-1996 time period for glaciated basins while non-glaciated basins showed neither positive nor negative significance in trends. They argue that negative trends indicate that the initial phase of increased meltwater production has passed for most of British Columbia. However, Jost et al. (2012) modeled glacier contributions to August and September flow in the Mica Basin, Upper Columbia, and found no significant change from 1972-2007. Glaciers in the CBTR span an elevation and latitudinal gradients and it is possible that while some glaciers have reached peak flow, those in the northern Mica basin have not.

Other Glaciers in the Western Cordillera

Long-term mass balance data is available for several glaciers across British Columbia, the Place and Helm glacier in the Pacific Coast ranges and the Peyto Glacier in the Canadian Rockies. All three glaciers indicate consistent negative mass balances from the late 1970s (Figure 5.2.2), showing cumulative average thickness losses of 25-35 meter water equivalents (m.w.e.) since 1980 (Demuth 2013). To put these glaciers in a global perspective, the World Glacier Monitoring Service reports that in the 2010/2011 balance year, the 37 global reference glaciers had an average thickness loss of one m.w.e, bringing the cumulative average thickness loss to more than 15 m.w.e since 1980 (WGMS 2013).

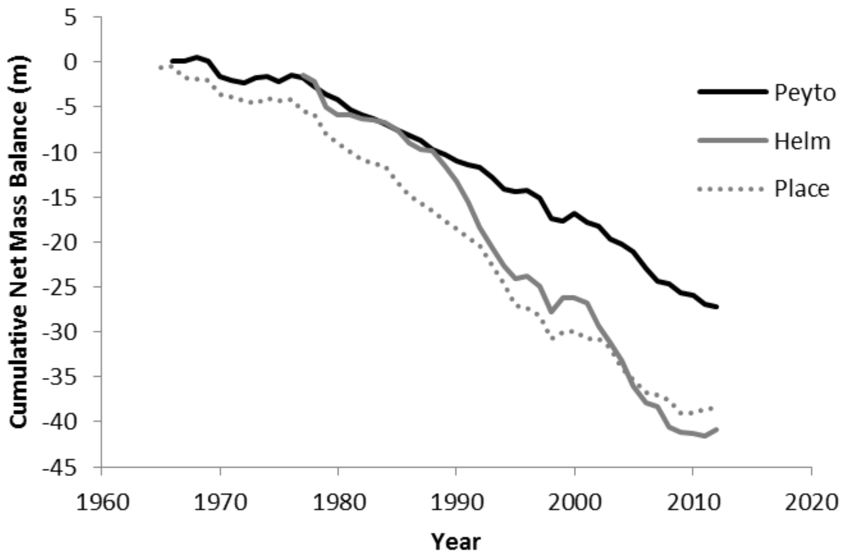


Figure 5.2.2 Cumulative net mass balance data for the three long-term mass balance reference sites in British Columbia. The Peyto Glacier is in the Canadian Rockies, and the Helm and Place Glacier are located in the Coast Ranges.

Methods

Streamflow analysis

Because Stahl and Moore (2006) do not show their results regionally or for specific stream we use a similar analysis here to reconstruct apparent changes in glacier contributions for glaciated streams in the CBTR. This analysis places the results of Stahl and Moore in the context of the CBTR region. We use the equation derived by Stahl and Moore (2006) to determine glacial contributions to August streamflow. This method involves fitting a regression equation to July discharge (carryover storage), mean August temperatures, and precipitation. The residual theoretically represents the glacial meltwater contribution. The equation is as follows:

$$Q_{Aug}(t) = b_0 + b_1 Q_{\mathrm{Jul}}(t) + \mathrm{b}_2 T_{Aug}(t) + b_3 P_{Aug}(t) + e(t)$$

Where t is the year, Q (m^3 s^{-1}) is mean discharge, T (^{0}C) is mean air temperature, and P (mm) is monthly precipitation. b_i refers to coefficients that are determined, and *e* is the residual – or the estimated glacial contribution, see Stahl and Moore (2006) for more details. August streamflow is used because glacial contribution should be most evident at this time since snowpack contributions are reduced. We apply this equation for all available hydrometric data for streams with greater than 2% glacier cover. In addition to the methods presented by Stahl and Moore 2006, we use the Broken Stick Regression method (Nave, 2010) to determine the onset of the decline in August flows; that is the year that the residual begins to decline from an otherwise non-significant trend.

Results

August residual streamflow

In the Upper East Columbia region we find significant declines in four of the six glaciated streams analyzed (Table 4.2.1). Gold and Kicking Horse streams show significant declines through the full period of record, while Blaeberry and Spillimacheen show significant declines beginning around the year 2000 (Figure 4.2.2). Canoe Creek showed non-significant declines from 2000, and Beaver Creek showed no trend through the period of record (1985-2011). Note that most of the streams reported are from the southern end of Kinbasket Lake as Canoe Creek is the only monitored stream in the upper reaches of the CBTR.

In the Upper West Columbia we see similar inter-annual variation as the Upper East Columbia, though the declining trend begins slightly earlier, with an average breakpoint date at 1984 (Table 5.2.1, Figure 5.2.3). The exception is Kirby stream, which shows a declining trend in the early 70s, followed by a stable residual flow. Apart from the Incomappleux, all declining trends were statistically significant at $p<0.05$. All residual time series from in the Upper West and Upper East Columbia statistical hydrologic regions show strong and significant correlations (Table 5.2.2).

Table 5.2.1 Broken stick regression results for the residual (glacier contribution) flow from glaciated streams in the Upper East and Upper West Columbia statistical regions.

Stream	Region	Record Length	Glacier Cover (%)	Break Year	Trend	Trend Signficance (*p*)
Blaeberry	Upper East	1966-2011	7.46	1999	Declining	0.05
Kicking Horse	Upper East	1973-2005	4.28	Full Record	Declining	0.01
Spillimacheen	Upper East	1951-1984,1995-2011	4.40	2000	Declining	0.01
Gold	Upper East	1973-2011	13.39	Full Record	Declining	0.05
Beaver	Upper East	1985-2011	7.86	Full Record	No Trend	0.26
Canoe	Upper East	1971-2011	19.08	2000	Declining	0.63
Kirby	Upper West	1973-2005	2.96	1985	Declining	0.4
Goldstream	Upper West	1934-2011	6.08	1990	Declining	0.02
Illecillewaet	Upper West	1964-2011	6.15	1999	Declining	0.06
Incomappleux	Upper West	1953-2005	10.56	1973	Declining	0.51
Duncan B	Upper West	1964-2011	7.77	1975	Declining	0.03

Table 5.2.2 Correlation matrix for residual flow (glacier contribution) from glaciated streams in the Upper East and West Columbia statistical regions

	Ille.	*Inco.*	*Duncan*	*Golds.*	*Canoe*	*Gold*	*Blae.*	*Beaver*	*Kick.H.*	*Spill.*
Illecillewaet	1.00									
Incomappleux	0.86	1.00								
Duncan	0.90	0.87	1.00							
Goldsream	0.85	0.77	0.80	1.00						
Canoe	0.73	0.79	0.79	0.65	1.00					
Gold	0.77	0.63	0.77	0.75	0.72	1.00				
Blaeberry	0.84	0.87	0.88	0.77	0.89	0.81	1.00			
Beaver	0.73	0.60	0.75	0.66	0.71	0.60	0.67	1.00		
Kicking Horse	0.81	0.76	0.85	0.80	0.77	0.74	0.86	0.60	1.00	
Spillimacheen	0.89	0.83	0.95	0.82	0.86	0.78	0.88	0.87	0.85	1.00

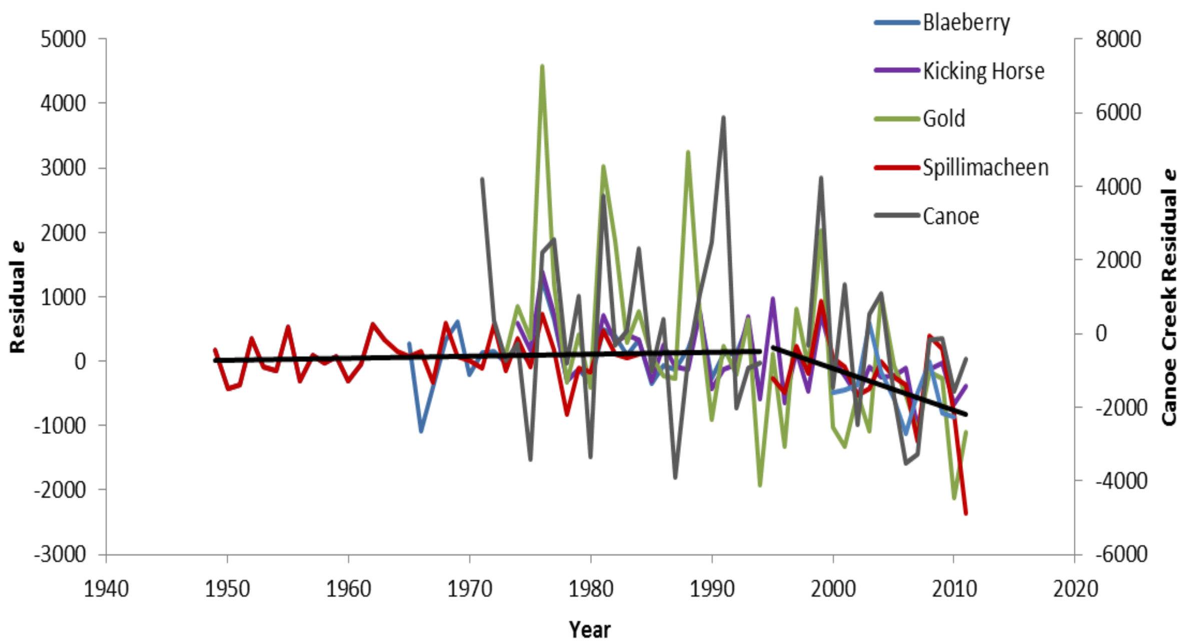


Figure 5.2.2 August residual streamflow (an estimate of glacier meltwater contributions) for 4 glaciated streams in the Upper East Columbia statistical region

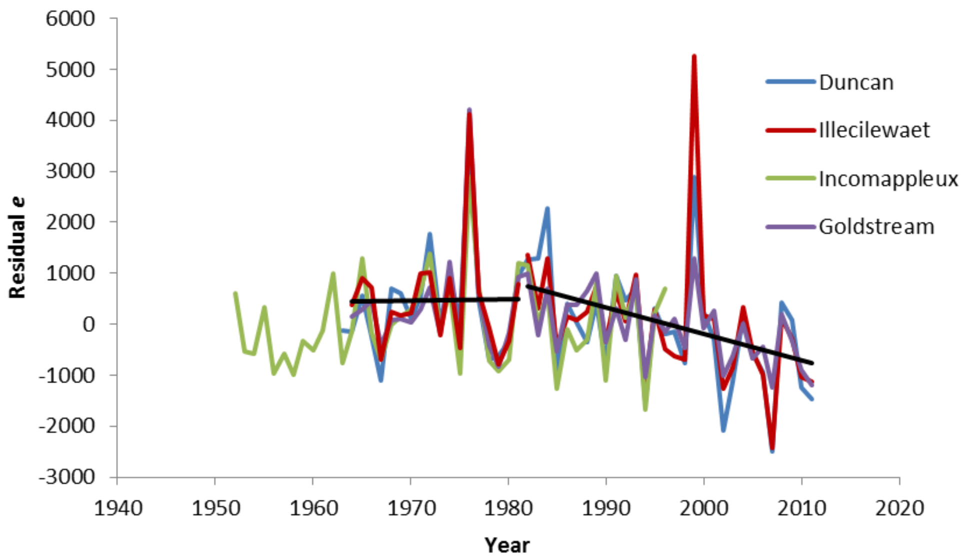


Figure 5.2.3. August residual streamflow (an estimate of glacier meltwater contributions) for 4 glaciated streams in the Upper West Columbia statistical region.

Discussion

A decline in glacier and snowpack resources is evident in recent decades. The results from the Stahl and Moore (2006) equation suggest that warming-induced increased discharge from glaciers has already passed and contribution are now declining. This is consistent with the strong multi-decadal declines in extent and area of the glaciers in the region, as well as the British Columbia reference glacier mass-balance data. However these results are in conflict with simulation results, which suggest glacier runoff in the Upper Columbia Basin will increase until mid-21st century (Schnorbus et al. 2012; Jost et al. 2012). It remains possible that the discrepancy between Stahl and Moore (2006) residual August flow and model simulations are a result of the poor availability of spatial streamflow data; only one of the streams analyzed for August Residual flow is in the northern reaches of the Mica Basin, and two of the most northerly streams (Beaver Creek and Canoe Creek) did not show significant declines in glacier contributions. Because it is unclear to what extent glacial contributions to streamflow have changed historically, there is considerable uncertainty in how they will respond in the future it both magnitude and direction (Schnorbus et al. 2012). This information is critical for future projections of streamflow from these glaciated basins, particularly for late summer flow when water resources are already limited.

An important question is whether or not the reduction of glacial contributions will be compensated for by the predicted increases in precipitation, though predicted increases are not expected to occur in August. Based on a recent study on the Illecillewaet glacier it seems unlikely. Hirose and Marshall (2013) estimate that with a 1^{0}C of warming, a net loss of 0.6 meter water equivalents will occur, and that a 30% increase in winter precipitation is required to offset this change. Using current simulations, winter precipitation is expected to increase by 8% (PCIC 2013). These estimates indicate that

reductions in glacial contributions to flow from the Illecillewaet Glacier are expected to decline. Similar data for other glaciers in the area are not presently available.

5.3 Summary of Data and Knowledge Gaps

There are considerable data and knowledge gaps with respect to the cryosphere creating barriers to the assessment of 1) the historical relationship between glacial meltwater contributions and climate and 2) high elevation snowpack changes, and 3) the relationship between glacier retreat and permafrost melting to slope stability and other geomorphic hazards. Because streamflow in the CBTR is dominated by snowmelt, the lack of spatially comprehensive information on snowpack above 2000 m and glacial resources translates into considerable uncertainty in the future projections of streamflow. Significant data gaps are as follows:

- Inadequate information on long-term glacier mass-balances and contributions to streamflow
- Inadequate understanding of the long-term relationship between climate and glacier response.
- Inadequate information on precipitation and snowpack/snow water equivalents above 2000 m. The area above 2000 m represents 30% of the CBTR and is critical for modelling the response to climate and for late season snow contributions. It would be ideal to combine areal coverage data and gradients in addition to point samples.
- There is only one glaciated stream monitored above the lower reaches of Kinbasket Lake (The upper ~ 120 km of the basin), Canoe Creek.
- There are no paired high elevation and low elevation stream gauges in glaciated basins.
- There are no long-term paired mass-balance and stream gauge sites in the basin.
- There is inadequate information on elevation gradients in winter precipitation and snowpack.
- There is little information on the trends in glacier mass balance across spatial gradients in the CBTR.
- There is little understanding on where the CBTR glaciers are with respect to peak runoff.
- There is a need to understand the impact of extreme temperatures and precipitation events on glaciers in the CBTR and how glaciers may moderate or exacerbate extreme events.
- There are several problems with data accessibility with respect to INFOEX data (at present being resolved) and glacier inventories.

5.4 Recommendations

1) Support monitoring programs and research that will provide a greater understanding of how glaciers have responded to climate change in the past so that models can effectively evaluate future changes under different climate change scenarios. Specific projects/tasks may include:

    a. Incorporation of high elevation snow data (INFOEX) and dynamic glacier models into regional and basin wide stream flow forecasts

    b. The addition of more sampling sites and the incorporation of areal measurements initiated through a research study

    c. Determination of current glacial contributions to flow as well as historical contributions using paleo-archives

    d. A continuation of Brian Menounos' work to determine area and volume changes of glaciers in the basin for the last 8-10 years. Initiate discussions with federal and provincial network managers to avert further reduction in the climate network of BC

    e. A life expectance analysis of glaciers in the CBTR

    f. Evaluating changing snowfall/snow water equivalent regionally and across elevation gradients

2) Continue to support and facilitate workshops with members of the Cryosphere Research Network to ensure the established priorities and tasks are seen to completion, e.g. the establishment of glacier supersites within the basin.

3) Continue to work with the Cryosphere Research Network on investigate opportunities for monitoring network growth, including the incorporation of citizen science groups.

4) Work with federal and provincial network managers as well as local universities to establish the monitoring of permafrost and permafrost degradation.

5) Assist provincial government with the identification and risk rating of glacier retreat and permafrost declines including outburst floods and mass wasting.

6) Initiate discussion with federal and provincial network managers, international groups (Global Land Ice Measurement from Space (GLIMS), and scientists to integrate and increase the availability of cryosphere related data. All should be reported along with flags that indicate quality parameters and should be housed on a central registry maintained by the federal or provincial government.

6.0 Groundwater

6.1 Data Availability and Coverage

Information on groundwater resources in the Columbia Basin Trust Region (CBTR) is sparse having received little attention from both government agencies and from academia. The lack of information is due to both low population densities, and because determining the extent of groundwater resources in this region is complicated by complex surficial geologies related to repeated glaciations (Livingston 2013; MacDonald 2009). There is likely a considerable amount of information available through consulting firms, however, these reports are rarely published and due to the transient nature of some firms, the information may be lost. At present, there are only five monitoring wells in the British Columbia Groundwater Observation Well Network (Table 6.1); the earliest was established in 1966 in Castlegar, and the most recent two were established in 2005. The Ministry of Environment monitors two wells for water quality in the Columbia Basin Trust Region, neither of which is in the Upper reaches of the Basin (Harma 2014)Due to the low density of groundwater monitoring wells, Wildsight and Living Lake Canada have initiated citizen-science groundwater monitoring programs. At present there are 8 wells being monitored by citizens for water depth and 3 for water chemistry. . Groundwater in the region is primarily used for commercial and domestic use, supplying many rural residents and communities with water (Figure 6.2), though use is not thoroughly documented as users are not required to report wells or withdrawals. Groundwater monitoring provides important information on regional water resources and environmental impacts. The lack of information of both groundwater resources and use leads to considerable data and knowledge gaps on both available resources and the potential impacts due to climate change.

Important distinctions between surface water bodies and groundwater are that 1) water moves through the subsurface at rates that are orders of magnitude longer than in surface waters. This means that once contaminated, recovery may take decades, centuries, or may not even be possible. 2) Long residence times of groundwater means that contact times between water and minerals are greater, and the dissolved constituents may make this water less suitable or desirable for irrigation or drinking water due to dissolved metals, or hardness.

Groundwater in the region is primarily used for commercial and domestic use supplying many rural residents and communities with water (Figure 3.1). The use of groundwater for drinking and irrigation may become more important in the future as the climate warming continues to alter the hydrologic cycle. Groundwater used for drinking from small systems (up to 500 people in a 24 hour period) and water supply systems (> 500 people) is inspected though the Interior Health Authority in all regions, though it is up to the water supplier to maintain the system and ensure its safety. Water quality reports from wells and water systems can be found on the IHA website. An existing problem is that water sampling is not always conducted at sufficient proximity to the water intakes particularly in the more

heavily populated regions (Nelson, Castlegar, Cranbrook, Invermere) (Roger Parsonage, IHA, personal communication).

Persons using private systems/wells are encouraged to have their own water quality tested. Though use from individual families is not thoroughly documented, users are not required to report wells or withdrawals. Because groundwater monitoring provides important information on regional water resources and environmental impacts, the lack of information of both groundwater resources and use leads to considerable data and knowledge gaps on both available resources and the potential impacts due to climate change.

Groundwater quality is subject to change as a result of land-use and human occupation. Common sources of localized pollution are cesspools, septic tanks, leaks in municipal systems, waste repositories, and industrial activities. Non-points source pollution, a more difficult problem to manage, may occur from agricultural activities (fertilizer, herbicides, and insecticides), toxic runoff from urban areas, sedimentation from land-use activities, bacteria or nutrients for pastoral activities, and atmospheric deposition. The efforts from Wildsight and LivingLakes to monitor what the government is not is commendable. In an effort to minimize their error they consulted with university professors and rely on university students to analyze the data. One potential pitfall from their methods is that they are using, by no other option, abandoned wells. Abandoned wells can have broken casings and are not regularly pumped, which can affect their results.

Groundwater in the CBTR

The most important aquifers in the region occur in the valley fills associated with the large rivers the drain the basin; groundwater can also be found within the mountain bedrock fractures (Parsons 2013)**.** The valley fills are generally composed of glacio-fluvial deposits comprising a complex network of high and low permeability sedimentary sequences (MacDonald 2009; Livingston 2013). In the mountain bedrock groundwater distribution is shallow and irregular and generally relate to fracture systems that mostly discharge to mountain streams and lakes (Parsons 2013). Hood et al. (2006) found that up to 74% of the total outflow in lake O'Hara (2026 masl) in the CBTR was due to groundwater contribution. Though the age of the water was not established, solute concentrations were substantially higher than rain, ice and/or snow concentrations measured, indicating the water had been in the subsurface long enough to sufficiently interact with minerals. These results suggest that although the most important aquifers in the region are likely those that occur in the valley fills, it may be important to explicitly consider the role of shallow and deep groundwater resources in the mountain regions and determine the year to year storage.

Table 6.1 British Columbia Groundwater Observation Wells within the CBT region.

Location	Well Number	Latitude	Longitude	Date Established
Castlegar	74	49°18'	117°36'	1966
Jaffray	362	49°22'	115°18'	2005
Cranbrook	291	49°28'	115°43'	1985
Wasa Lake	363	49°47'	115°44'	2005
Golden	309	51°15'	116°55'	1989

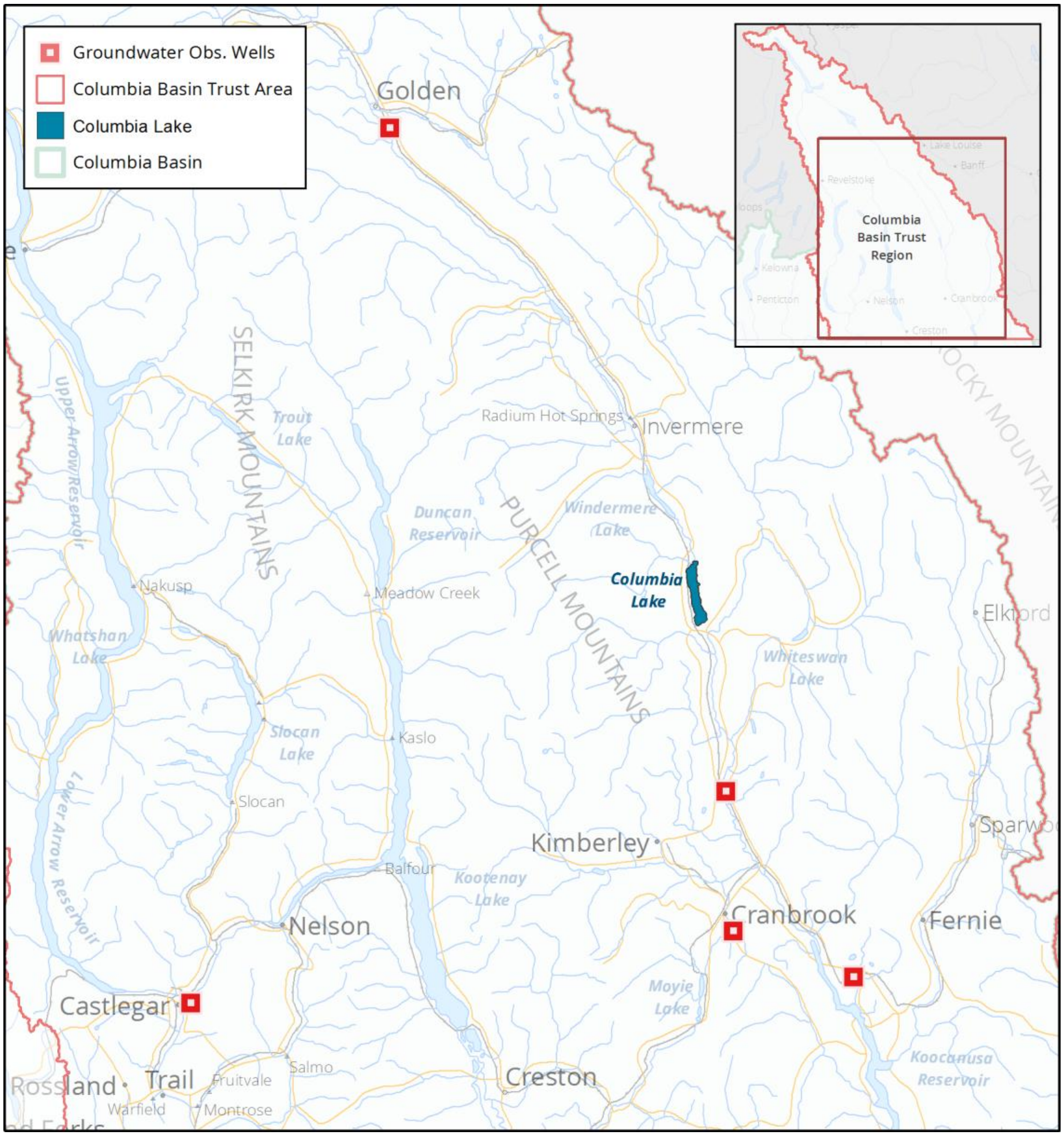


Figure 6.1. Map of the 5 groundwater monitoring wells.

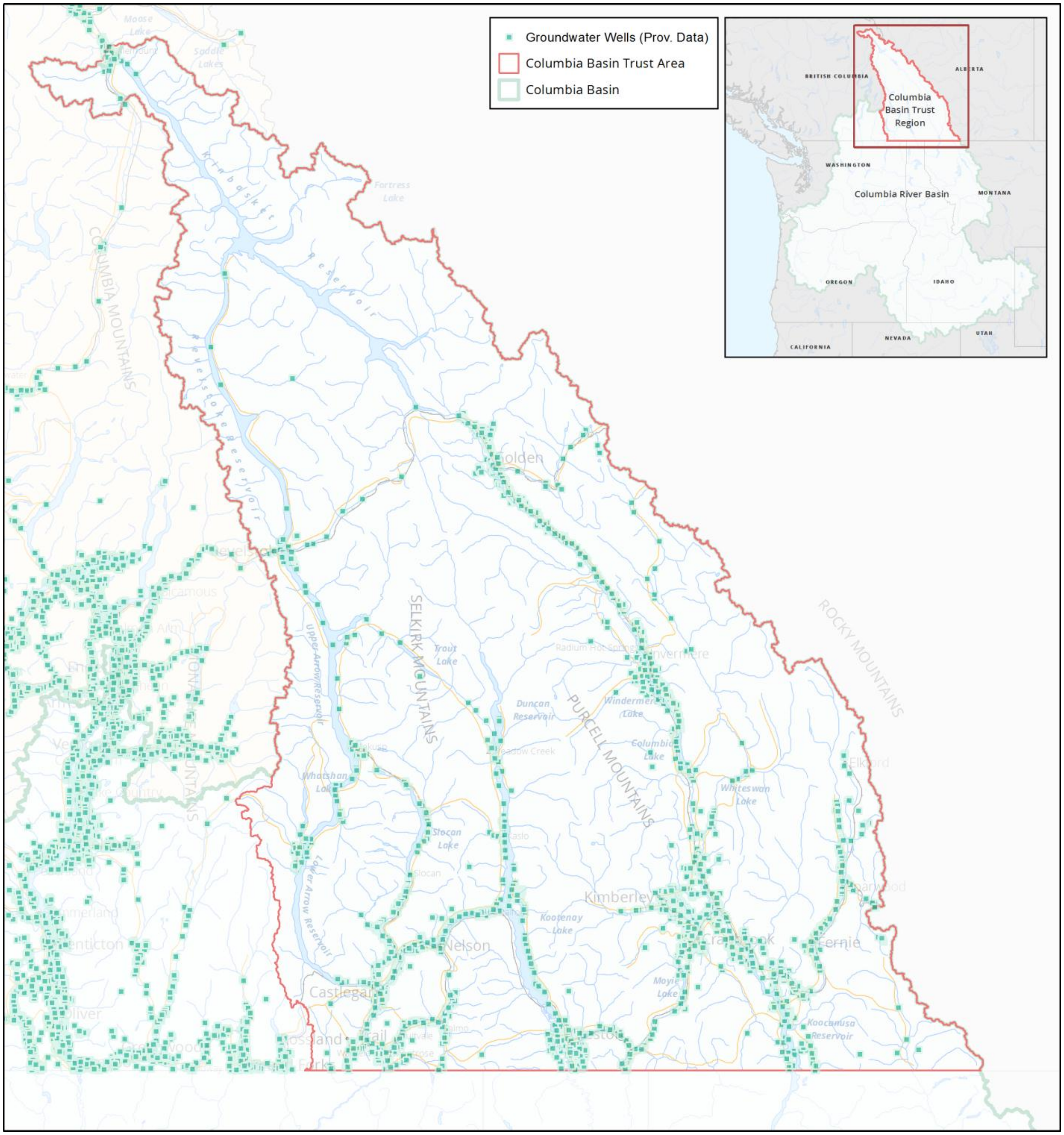


Figure 6.2 Map showing well locations in the Provincial database

Groundwater in the Upper Columbia Region

MacDonald (2009) conducted an analysis on groundwater resources and use for the Upper Columbia River valley between Canal Flats and Edgewater. The analysis determined that most of the

commercial, municipal, and residential withdrawals occur from the shallow subsurface. Confined shallow aquifers have relatively low water yield, while alluvial aquifers have higher yield. Alluvial aquifers are strongly tied to surface water flows, and deeper resources are undesirable due to high heavy metal and carbonate concentrations (MacDonald 2009). Given that shallow alluvial aquifers are directly under the influence of surface water conditions, specifically precipitation and runoff (MacDonald 2009), these resources are vulnerable to climate change and land use impacts.

During the summer, groundwater-dominated mountain streams are very important for the survival of aquatic organisms. This is largely due to the fact that at high temperatures fish may experience reduced growth associated with depleted oxygen, appetite, and enzyme efficiency. In extreme cases, fish can die when thermal tolerances are exceeded. Therefore, the temperature of the water, particularly cool water associated with groundwater upwelling during summer, controls habitat selection of many fish (Power et al. 1999). Cunjak (1996) suggests the protection against extreme abiotic conditions such as ice, reduced oxygen and streamflow fluctuations during winter periods are also critical to fish survival. Groundwater upwelling enables fish to overwinter in streams which would not otherwise contain suitable habitat in the absence of the relatively warm, oxygenated water provided by groundwater (Brown et al. 2011). Changes in groundwater regimes of the CBTR as a function of climate and land use change have important consequences for ecosystems and suggest this sensitive water-resource must be accounted for when adaptively managing these systems.

6.3 Climate Change Impacts

It is unclear how, and to what extent, climate change will likely affect groundwater resources in the CBTR. This is because climate change is expected to alter precipitation type and amount, surface water resources, and evapotranspiration rates, all of which can be expected to influence groundwater resources directly, through changes in recharge, and indirectly through changes in human withdrawals (Green et al. 2011). Current and future reductions in snow accumulation (Barnett et al. 2008) and glacial ice (Jost et al. 2012) have been shown to result in reduced water supply in the Columbia basin, particularly for the low flow summer periods (Burger *et al.*. 2011). Huntington and Niswonger(2012) have demonstrated that shifts towards an earlier onset of spring runoff can result in decreased groundwater contribution to streamflow. All of which can potentially influence groundwater-surface water interactions.

Because streamflow in the CBTR is snow-melt dominated and fall precipitation can be scarce, late summer stream flows are highly dependent on glacier and groundwater contributions. In drier months, groundwater can comprise up to 35% total late-season flow in many small streams in the CBTR (Jost et al. 2012). Glacier resources are expected to decrease in a warming climate with complete losses of some glaciers occurring in the next 50 years depending on the current size, latitude, and elevation (Trubilowicz 2010). Groundwater resources will therefore become increasingly important as glacier resources are lost across the basin, in particular to late summer flows when water resources are already limited.

Increased evaporation rates and declines in late summer water availability can lead to declines in groundwater levels. These declines could reduce discharge to surface streams and lakes and/ or increase seepage losses from surface water bodies to groundwater systems. A climate change sensitivity analysis conducted for the Grand Forks aquifer (Figure 5.1) indicated that the water-table was more sensitive to changes in river stage elevation than changes in recharge (Allen et al. 2004), similar to the Upper Columbia River Valley (MacDonald 2009), and may be true for other valley fill aquifers through the CBT region.

6.4 Summary of Data and Knowledge Gaps

- There are only two wells being monitored for groundwater quality.
- Climate change and land use impacts are at present unclear and a comprehensive list of vulnerable locations has yet to be identified.
- Water sampling through the IHA is mainly conducted on treated samples and there is little information on raw water quality.
- Water sampling should occur closer to the intake sources, particularly for the large cities in the region (Castlegar, Nelson, Cranbrook, and Invermere).
- There are issues with obtaining comprehensive and complete water quality data for a region or system.
- High metal concentrations in some of the EC monitored streams indicate that groundwater metal concentrations may be high, though it is not clear at present.
- There is a general lack of information on the location, age, and extent of groundwater resources in the CBTR.
- There is a general lack of information on groundwater use in the region.
- Climate change and land use impacts are at present unclear and a comprehensive list of vulnerable locations has yet to be identified.
- Large areas of the CBTR do not have monitoring wells. (see figure 5.1.)

6.5 Recommendations

1) Support the conduction of regional water supply and demand studies accounting for current and future water use as well as projected climate change impacts. This will require the following information,
    - Regional delineation of aquifers
    - Regional accounting of current groundwater use

- Climate change sensitivity analysis for aquifers (modelling)
- Expansion of groundwater monitoring well network as appropriately determined
- Use water chemistry and isotope analysis to identify source water for streams.

2) The analysis conducted by MacDonald et al. (2009) found and highlighted data and knowledge gaps with respect to groundwater resources and provided recommendations. These are included below and it is recommended that similar detailed analysis be conducted by hydrogeology consulting firms and/ or researchers for the remaining regions in the CBTR.

   Upper Columbia River Valley

   - Information on current and future water use (irrigation, snow making, human consumption)
   - Monitoring of primarily groundwater fed streams, including the reinstatement of monitoring of Windermere Creek
   - Monitoring of surface water resources, specifically large watersheds on the eastern side of the valley
   - Reinstatement of the monitoring station Columbia at Fairmont and/or a water level station at Columbia Lake

7.0 Major Assessment Gaps

7.1 Atmospheric Contaminants

Wet and dry deposition have the potential to affect water quality through the alteration of precipitation pH (Brahney et al. 2013), transport and deposition of nutrients (N,P)(Brahney et al. 2014), pathogens (Griffin and Kellogg 2004) , organic contaminants (Blais et al. 1998), and heavy metals (Lawrence and Neff 2009).

7.1.1 Wet deposition

The deposition of acid precursors has received considerable attention in the eastern provinces and states for decades and in general conditions are improving (Schindler 1988; Waller et al. 2012). More recently, industrial growth in western North America has led to concerns over rising acid, and in particular reactive nitrogen (NOx) deposition in the western US (Byron 1991; Wolfe et al. 2001). In western Canada, emissions of NOx increased by 29% from 2000, and are expected to increase a further 5% by 2020; ammonia emissions are expected to increase by 50% during the same time (Schindler et al. 2006). In western Canada, NOx emissions are predominantly from vehicle and oil and gas industry emissions and ammonia emissions from agricultural practices. One study suggests that deposition rates in the Canadian Rocky Mountains of Alberta are comparable to deposition rates in the US Rocky Mountains (Lafrenière and Sinclair 2011) where considerable ecosystem effects have occurred (Baron 2000; Wolfe et al. 2001; Wolfe et al. 2003). Increased dissolved inorganic nitrogen in lakes and streams can potentially increase productivity, shift algal assemblages, reduce drinking water quality and can have toxic effects on the aquatic community. Acidification of lakes and soils associated with N deposition can increase dissolved heavy metal concentrations and harm aquatic biota. Regions in the CBTR with granitic and metamorphic bedrock are more sensitive to acid deposition than regions underlain by carbonate rocks, which have a greater capacity to ameliorate the effects of acid deposition. Melting glaciers may potentially increase nutrient loads though may enhance nitrogen flux through both the release of contaminants deposited via precipitation onto the glacier and from microbial processes in newly deglaciated terrain (Saros et al. 2010).

In addition to nutrient and acid deposition, of growing concern is the deposition of persistent semi-volatile organochlorine solvents and agricultural pesticides, particularly in conjunction with melting glaciers (see section). Remote, cold, and high elevation regions are disproportionately susceptible to deposition of these compounds due to cold condensation effects. Because these compounds are more volatile in warmer regions, then have a tendency to condense at both higher latitudes and higher altitudes. Data from the Alberta Rockies indicate a 10 to 100 fold increase in these compounds in the snowpack from 770 to 3100 m.a.s.l (Blais et al. 1998; Lafrenière et al. 2006). Daly et al., 2007 looked at air, soil, and lichen contaminant profiles in Mount Revelstoke, Yoho, and Banff National Parks. They

found reasonably consistent contamination in atmospheric measurements across all regions, but higher soil contamination in Revelstoke, likely due to cold-condensation effects and the proximity to roads (Daly et al. 2007; Choi et al. 2009). The specific ramifications of these compounds in the CBTR are not entirely clear, though many of these compounds are potential human carcinogens, and can be harmful to aquatic species.

7.1.2 Dry deposition

Recent analyses have indicated that dust emissions are increasing in eastern Washington and northern Montana (Brahney et al. 2013); depositional regions likely include the southern portions of the Columbia Basin Trust region. Dust acts as a vector for the transport of agricultural pesticides (Griffin et al. 2001) as well as pathogens, potentially affecting human and ecosystem health (Griffin and Kellogg 2004). Heavy metals may also be concentrated through adsorption onto dust particles during transport (Morselli et al. 2003; Marx et al. 2005; Lawrence and Neff 2009). Several heavy metals are nutrients needed for enzyme production (Fe, Mn, Cu, Zn, Co, Mo, and B), though many of these same elements, along with a few others (Hg, Pb, Cd, Ag, As), can be toxic to aquatic organisms at relatively low concentrations (Rainbow 2003). Dust may also contain acid neutralizing carbonates, and nutrients (P) in both the organic and mineral fractions. Though it is not likely that pathogens and heavy metals are a concern in the CBTR, the transport of pesticides (as discussed above) and nutrients may negatively impact water resources in the region. The concentration of P has strong implications for species composition and trophic interactions across all aquatic habitats; in naturally oligotrophic mountain systems, small changes in these nutrients can cause the proliferation of nuisance species (Kirkwood et al. 2007), toxic species (De Figueiredo et al. 2004), and species of low nutritional value (Brahney et al. 2014). In addition, dust transported in the winter affects snow albedo, and in regions of Colorado has affected the timing of streamflow with implications for plant phenology (Painter 2007).

7.2 Water quality effects of the melting cryosphere

Water quality and availability is arguably one of the most important issues facing society in the present century. One half of the world relies on freshwater from mountain systems (Unesco 2009). Glaciers supplement snowmelt runoff in late summer for many mountain drainage basins. However, glaciers are retreating at unprecedented rates, and winter snow cover is expected to thin and melt earlier in the decades to come (Barnett et al. 2005; Barnett et al. 2008; Viviroli et al. 2011). These hydrologic changes will reduce late-summer surface runoff and could negatively impact sensitive aquatic ecosystems through altered flow regimes, sediment and nutrient fluxes, water temperature, and light characteristics.

Glaciers serve a variety of critical physical, hydrologic, and biogeochemical functions for mountain watersheds. Since 1985, glaciers have declined by 15% in the Columbia Basin of Canada (Bolch et al. 2010), and recent studies indicate that most glaciers in western Canada and the US will disappear by the end of this century (Marshall et al. 2011; Vaughan 2013; Radić et al. 2014). As of 2008, glaciers cover only

2.6% of the total area yet can contribute up to 35% of the late summer flow (Jost et al. 2012; Hirose and Marshall 2013). This late summer period coincides with high human demands for energy, irrigation, and domestic use. Low flows at this time can have negative consequences for these human needs and for aquatic organisms due to increased water temperatures and the reduction in available habitat (Moore et al. 2009). In addition, there is little to no information on the biogeochemical and water quality effects of glacier recession in the Columbia Basin of Canada.

Of particular importance to alpine environments and downstream ecosystems are the changes in nutrient concentration (P, N, Ca) and flux as well as sediment loads. Glaciated basins can have high yields of inorganic P from poorly weathered apatite rich mineral phases (Filippelli et al. 2006) and the retreat of glaciers may enhance nitrogen flux through both release of contaminants deposited via precipitation onto the glacier and from microbial processes in newly deglaciated terrain (Saros et al. 2010). Data from the Environment Canada water quality network indicate that nitrate concentrations in glaciated streams are six times higher than those draining unglaciated terrain in the Basin. Because alpine aquatic ecosystems are naturally oligotrophic (low-nutrient), small changes in nutrient concentration can translate into large relative change in nutrient availability. The concentration of N to P has strong implications for species composition and trophic interactions across all aquatic habitats; in naturally oligotrophic mountain systems, small changes in these nutrients can cause the proliferation of nuisance species (Kirkwood et al. 2007), toxic species (De Figueiredo et al. 2004), and species of low nutritional value (Brahney et al. 2014).

Considerable changes in flow regimes and sediment flux can also be expected. With the loss of glacier resources, a reduced sediment load and increased water temperature and channel stability can be expected (Moore et al. 2009). Through glacier fed streams tend to have and lower overall species richness as a result of high sediment loads and cold temperatures, these conditions are favoured by several, now suspected endangered, invertebrates (Hylander et al. 2011; Jacobsen et al. 2012). Late summer cool glacial waters also maintain flow and cooler temperatures needed by cold water fish. Finally, runoff from melting glaciers tends to have higher concentrations of organochlorine and polychlorinated biphenyl contaminants, including those that have been out of commission for decades (e.g. DDT) (Blais et al. 2001). As a result fish and other biota in glacier fed streams and lakes tend to have higher concentrations of these contaminants (ibid).

7.3 Invasive or Bloom forming Species

The BC Ministry of Environment, BC Fisheries, and Fisheries and Oceans Canada keep track of invasive species observations and can be downloaded from the FISS database. As with all water quality data, the information is distributed across many different databases, personal computers, and agencies. As such it can be difficult to determine what is or is not in any given water body or watershed. In an effort to remedy this, an endeavor to incorporate all the data into one database is underway for the province; this will allow users to find the information for a single watershed in a single database.

Invasive species that have the potential to affect water quality include algae, aquatic plants, riparian plants, and fish. In addition, certain native bloom forming species, such as *Didymophenia Geminata* (rock snot), can affect water quality and habitat during blooms. Information and management plans for invasive plants are more established than for invasive fish or algae; for example, FLNROs has an invasive plant program that includes management, prevention, and mitigation. At present the province employs only one invasive species coordinator (Matthias Herborg, MoE), creating challenges with resources both in terms of manpower and financial support. This lack of resources makes it difficult to not only monitor all invasive species, but to understand the environmental or water quality implications of introduced species.

7.4 Cumulative Effects Monitoring

Cumulative effects monitoring takes into account multiple stressors on a system for defined valued ecosystem components. An extensive cumulative effects model for a management framework is underway in the Elk Valley lead by Stella Swanson of Swanson Environmental Strategies. The project initiated discussions amongst various stakeholders from the valley including government and industry representatives. These discussions lead to a compilation of specific unanswered questions by regional managers as well as an agreed upon list of the valued ecosystem components (habitats or species) on which to focus the model. Based on the success of this effort, the province has created a full-time position out of Cranbrook to apply the model more broadly. The principals behind the models can be widely applied and the lack of this type of assessment more broadly was noted by almost every water professional that contributed to this making of this report.

7.5 Pharmaceuticals, Pesticides, and other Organic Contaminants

Landscape development including agriculture, golf courses, industry, mining, urbanization, as well as atmospheric deposition has the potential to bring contaminants in the water systems. At present the sewage systems and water treatment operations in the CBTR do not treat or sample for pharmaceuticals and other organic contaminants, most water treatment plants across the country do not. Nonetheless, this is a data and knowledge gap with respect to water and habitat quality.

In 2012 CRIEMP published a report on polybrominated diphenyl ether (PBDE) concentrations in fish and sediments. As part of this study, intensive sampling was conduced in the lower Columbia River over a 20 year period. Concentrations in mountain whitefish increased through the 1990s to mid 2000s, which was then followed by a smaller decline. For more details, please see the 2012 report (www.criemp.org).

7.6 Summary of Data and Knowledge Gaps

- Inadequate information on atmospheric deposition (wet and dry).

- Inadequate information on long-term glacier mass-balances changes and associated changes in stream chemistry.
- Short duration of most stream chemistry data sets makes it difficult to evaluate changes in permafrost or glacier recession.
- Instantaneous sediment load measurement through the Water Survey appears to have been cancelled (or no longer available online), and this information is important for evaluating changes in sediment flux from glaciated basins.
- Invasive and bloom forming aquatic species reporting, monitoring, and control
- Inadequate information on the concentration of pharmaceuticals, pesticides, and other organic contaminants in all water bodies in the CBTR
- The lack of legislation for invasive species in the Province

7.7 Recommendations

- Support monitoring programs and research that will provide a greater understanding of how climate change, glacier recession, and impoundments have affected and will affect water resources and ecosystem services.
- Work with local and federal government and academic scientists to establish an atmospheric monitoring program.
- Work with universities to understand critical changes to the environment through the climate and invasive species, particularly through masters or doctoral theses.
- Work with government and universities scientists to evaluate and measure organic contaminants in CBTR and to understand the potential risks.
- Work with government agencies and citizen science groups to establish programs to report and monitor invasive and bloom forming species.
- Support the establishment of more rigorous laws against the transport of invasive species contaminated boats and other water vehicles from entering the province.
- Work with developers, federal and provincial managers to include citizen science software; for example smart phone applications for invasive species monitoring.
- Facilitate the incorporation of cumulative effects models more broadly in the CBTR. This includes initiating programs that will define valued ecosystem components, baseline conditions, as well as environmental thresholds. This also includes supporting research in the development of environmental indicators, historical conditions, and environmental thresholds.

8.0 Overarching Gaps and Recommendations

Here we present the major and overarching data and knowledge gaps identified in this study. Additional and specific data and knowledge gaps for each water resource type and can be found in the "Summary of Data and Knowledge Gaps" and "Recommendation" subsections throughout the document (see Table of Contents).

8.1 Data Access

Access to data was a strong limitation in almost all water resource types investigated, particularly with respect to water quality. Water chemistry from both the federal and provincial data is easily accessible through web resources, as was the biomonitoring data from the Columbia Basin Watershed Network (CBWN). However, there is an abundance of knowledge and data in the basin not housed in an easily accessible online resource. In addition CABIN data is only available to partners and requires training at some cost. There is an abundance of government data collection and research that is not reported to any online resource. At present, there is no easy method to present or host these data online and there may be a lack of motivation and/or obligation to do so. Similarly, there is an abundance of consulting firms with data and analyses that also remain private. The latter is particularly problematic when resources are spent repeatedly to conduct the same analyses in the same region. We therefore recommend initiating discussions/workshops with federal and provincial network managers, regional consulting firms, businesses, and non-governmental organizations (e.g. stewardship societies, Canadian Avalanche Association, etc.) to integrate and increase the availability of water resource data. Consulting firms should be encouraged to publish their documents and make their data available. Ideally, these data should be housed in a central registry maintained by the federal or provincial government. Further, to facilitate the incorporation of data collected by the many valuable watershed stewardship societies in the CBTR, flags indicating quality parameters, collection methods, etc. should accompany all data. This will allow a query user to define and control the amount and disposition of data they use based on their individual need. US government agencies and government-funded programs/ organizations have strict guidelines for data accessibility to the general public and therefore have numerous data management platform examples to draw from.

8.2 Data Gaps

The current observational network is lacking in spatial representation and certain data types; this presents a barrier to fully understanding the ongoing changes in water quantity across the basin. Though there are various factors that contribute to the amount of data collected in any given region, including population density, objectives, financial support, and access to remote locations, there are considerable financial, social, and economic implications of not having enough data, particularly in the CBTR where water resources are of paramount importance. These gaps in data and knowledge lead to problems with

water resource allocation and management. In light of the upcoming renegotiations of the Columbia Basin Treaty, a critical knowledge gap is our understanding of the timing and volume of future water resources. A prime example: current hydrologic model projections indicate increases in peak and annual flow, largely due to the climate parameters that predict an increase in winter precipitation at high elevations. There are no current data to validate changes in winter precipitation at high elevations, and further, despite regional increases in precipitation stream yield is declining. As such, we do not know if we are managing to reality, or a flawed projection. In addition, there is virtually no information on permafrost in mountain regions and much to understand with respect to the changing climate and the cryosphere. Additional major gaps include evaporation, groundwater resources, small watersheds, and data from under-represented regions including the upper 120 km of the basin and elevations above 2000 masl. The latter represents approximately 30% of the basin's area. Making recommendations for specific sites to monitor is beyond the scope of this analysis as it would require additional data and field analyses.

To address these gaps we recommend the following,

1) Initiate discussions with federal and provincial network managers to avert further reductions in monitoring networks.
2) The organization of workshops between various data users to initiate discussion on data need for environmental effects analyses and monitoring, engineering, natural resource management, and resource allocation. The Cryosphere Research Network is an excellent example of a successful collaboration between data users and data providers.
3) Continue to support local stewardship groups in data collection. The ability for the local residents to take active roles in environmental stewardship is empowering and important for the morale of community members.
4) Recognizing that there are likely government funding restrictions on initiating new monitoring stations we suggest
    a. Due to the regional high-profile nature of the CBT and existing relationship between the CBT and the various water resource data end-users, we recommend that the CBT take a leadership role in data education and promotion as well as in the recruitment of contributors. Potentially through the organization of workshops and/or research networks including stewardship groups and businesses that benefit from data availability. The Farmwest approach to encouraging farmers to establish climate stations on their property in exchange for applicable data (real-time evapotranspiration estimates, corn heat units in degree days, etc.) is an excellent example. The former Ministry of Sustainable Resource Management's business review (Azar et al. 2003) is also an excellent resource for this type of initiative.
    b. Opportunities to enhance the existing network as well as the technology used can be gained by partnering with research groups. Once a station is established through research protocol, federal/provincial agencies may opt to provide maintenance support. For example, the establishment of the Parks Illecillewaet mass balance monitoring station was initiated through a short-term research project.
    c. Assist local governments with the identification and risk rating of drought, flood, debris flow hazards to determine metrics required and to establish appropriate monitoring stations in these areas.

There is a general need for water resource managers and academic scientists to communicate more frequently and effectively in order to find solutions needed for growing water concerns. The Columbia River Integrated Environmental Monitoring Program (CRIEMP) initiative is an excellent platform to establish a list of the most crucial research and development needs. CRIEMP is composed of federal and provincial government, local industry, First Nations, NGOs, and university partners. From this partnership, appropriate research directives can be formulated and additional operational and management tools can be developed. CBT can facilitate these partnerships through the organization of workshops and/or research networks including federal and provincial monitoring agencies, stakeholders, and researchers to identify the needs for climate and hydrometric projections, environmental effects analyses and monitoring, engineering, natural resource management, and resource allocation.

Because the quality of water affects a variety of ecosystems and human services, an effective water quality management scheme includes a monitoring program that evaluates water safety for use (drinking, aquatic life and wildlife, agriculture, recreation, industry), as well as for the maintenance of aquatic and terrestrial species and for habitat function. The Ministry of Environment has a relatively comprehensive water quality evaluation scheme to meet these objectives. By their own definition "Objectives are prepared only for those waterbodies and water quality characteristics that may be affected by human activity now or in the near future"; strictly speaking this does not include the effects of climate warming on northern regions that are relatively unpopulated. In addition because objectives through MoE are site-specific and designed to protect the most sensitive water use in the region, a spatially and representative long-term monitoring program is limited. Long-term monitoring occurs through the federal water quality program, though streams monitored are generally large and of transboundary importance. Recognizing that there are government funding restrictions to the types of data collected and the regional network density, community groups have stepped up to the plate to fill these gaps, specifically with groundwater and lake water quality monitoring. Though these efforts are important and commendable, ecosystem monitoring should be a government responsibility. That being said, various factors will contribute to the amount of water quality related data in any given region, including population density, data collection objectives, financial support, and access to remote and difficult terrain. However, there are considerable financial, social, and economic implications of not having enough data or knowledge.

8.3 Data does not equate to Knowledge

Despite the immense importance of the Columbia Basin in Canada, the region remains remarkably understudied by both the government and academia. Understanding the controls on water availability across the basin is crucial for maintaining ecological integrity, water security, and to meet the economic and hydroelectric needs of the basin and the international community. To quote from Azar et al. (2003) "Water is the 'great' resource of British Columbia. Maximizing the benefit of water, and minimizing its occasional harm, requires knowledge of the resource". It is important to recognize here that while data

collection and management are crucial to acquiring knowledge, these activities, in themselves, do not create knowledge. Both high level expertise and financial support are required to use data to produce knowledge, and further to turn the knowledge into motivation for action. The absence of an academic research institution and ongoing cuts to funding, staffing, and the retirement (without replacement) of hydrologic positions in the federal and provincial sector has led to a lack of high level expertise in the region, presenting a large and critical knowledge gap for water resources in the CBTR.

Data and knowledge gap reviews are useful for establishing need, garnering interest, and providing leverage for change; however, data, data needs, and knowledge are inherently fluid and the dedicated role of a water scientist in the basin should not be transient. We therefore recommend that the CBT initiate discussions with federal and provincial government for the maintenance/creation of water resource professionals (operational and research) and/or initiate discussion with regional universities for endowment and collaboration. These positions would help rectify many if not most of the identified knowledge gaps as well as to create synergistic collaborations with US jurisdictions and help local citizen stewardship groups maintain data integrity through appropriate training. In addition, the potential for the Columbia Basin to serve as a research focal point in understanding water resources and their management is immense and invaluable to Canada and the international community. This ultimately requires a coordination of efforts including networking, data sharing, and a platform for higher education and research, including the designation of a supersite or sites that monitor a suite of environmental variables. There is a strong precedence for this in the United States with the Long Term Ecological Research Network and the National Ecological Observation Network, groups which partner with universities and federal and state programs. These types of initiatives would certainly help address the knowledge gaps outlined in this review, as well as to create opportunities for leadership in the areas of watershed research and management.

8.4 Overarching Recommendations

- Leadership in education. Due to the regional high-profile and existing relationship between the CBT and the larger Columbia Basin Community, we recommend that the CBT take a leadership role in community education about water resources and the importance of maintaining healthy waterways.
- Educate local communities on the socio-economic importance of hydrometric monitoring and provide resources for the establishment of stream gauges and maintenance. This is potentially critical for groups like CABIN, where stream chemistry data is collected but volumetric data is often not available, which considerably diminishes the value of the data in the long term.
- Leadership in data sharing. Initiate discussion with federal and provincial network managers to integrate data collected by other agencies in the CBTR. All should be reported along with flags that indicate quality parameters and should be housed on a central registry maintained by the federal or provincial government.

- Leadership in bridging the research-implementation (knowing-doing) gap. Potentially through the organization of workshops and/or research networks including federal and provincial monitoring agencies, stakeholders, and researchers to identify the critical knowledge and data gaps, identify pressing management questions, and form research plans and working groups to address these issues.
- Support community monitoring programs. Investigate opportunities to enhance the existing network through local citizen science groups, businesses, and/or collaborations with research groups and government authorities. The ability for the local residents to take active roles in environmental stewardship is empowering and important for the morale of community members.
- Support monitoring and research programs that will provide a greater understanding of contemporary, historical, and future aquatic environments including streams, wetlands, lakes, groundwater, and reservoirs.
- Avoid further reductions to the hydrometric network of BC.
- Support research and investigations on climate related effects in water resources in small watersheds with elevated sensitivity to change.
- In general we recommend an ecosystems services approach to managing water with a more explicit and integrated system for understanding the tradeoffs and choices for decision makers. The present management scheme that focuses on point sources and areas of interest leaves gaps in changes related to diffuse sources of contamination including atmospheric deposition, land use, climate, fires, invasive species, and bloom forming species.
- Facilitate the incorporation of cumulative effects models in heavily populated and heavily used areas of the CBTR. This includes initiating programs that will define valued ecosystem components, baseline conditions, as well as environmental thresholds. This also includes supporting research in the development of environmental indicators, historical conditions, and environmental thresholds.

Glossary and Abbreviations

CBTR: Columbia Basin Trust Region (Figure 1.1)

ENSO: El Niño/Southern Oscillation

MAP: Mean Annual Precipitation

MAT: Mean Annual Temperature

NOI: Northern Oscillation Index

PDO: Pacific Decadal Oscillation

Climate Indices/Climate Modes: A climate index or climate mode is a calculated value that can be used to describe the state and changes in the climate system.

Meter water equivalence: The average thickness gained (positive mass balance) or lost (negative mass balance) from the glacier during a particular year.

Nival: of relating to, or characteristic of a region with snow

AO: Arctic Oscillation

PNA: Pacific North American Pattern

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Appendix

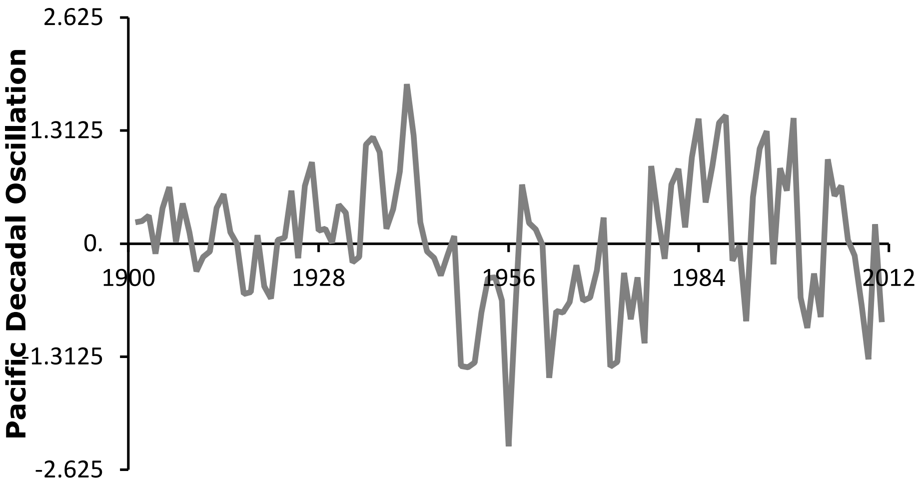

Figure A1 Time series of the Pacific Decadal Oscillation (PDO) as averaged from July to June.

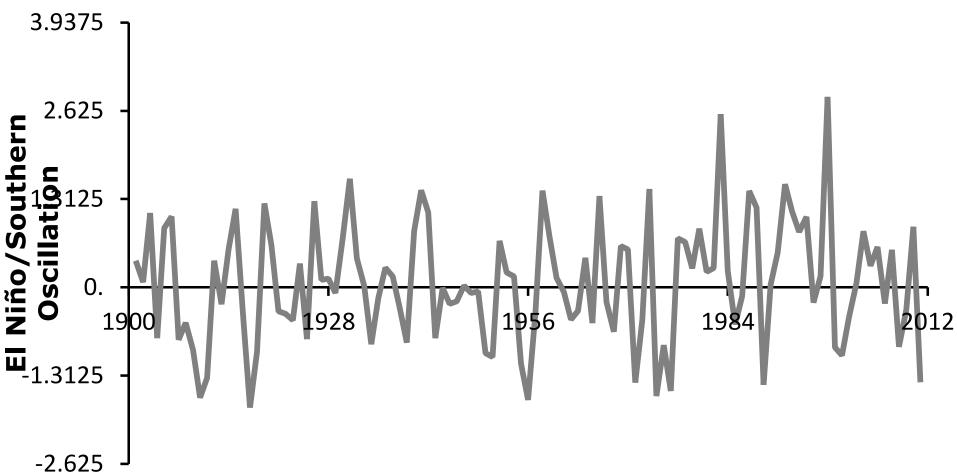

Figure A2 Time series of the El Niño/Southern Oscillation (ENSO) as averaged from July to June.

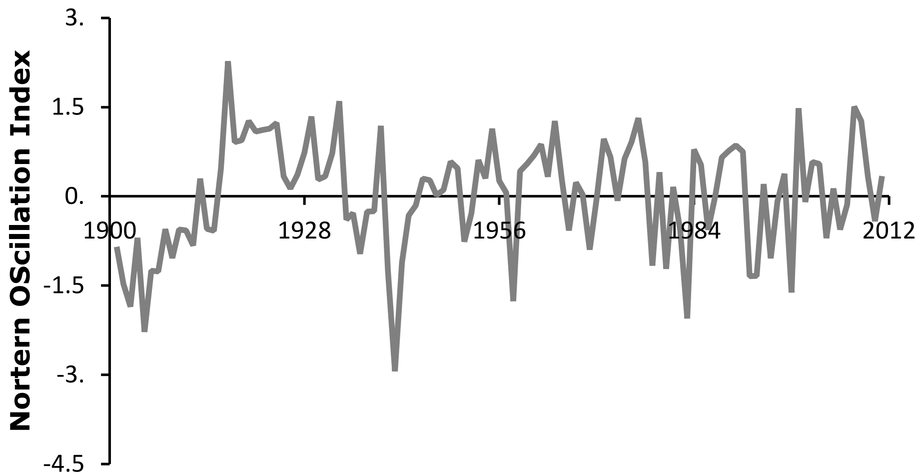

Figure A2 Time series of the Northern Oscillation Index (NOI) as averaged from July to June.