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Changes in the hydrological regime in the Upper Bow and Upper Athabasca Watersheds during the 20th century

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Graduate Program in Geography
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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CHANGES IN THE HYDROLOGICAL REGIME IN THE UPPER BOW AND UPPER ATHABASCA WATERSHEDS DURING THE 20TH CENTURY

(Spine Title: Hydrological change in the Bow & Athabasca Basins: 1911-2005)

(Thesis format: Monograph)

by

Heather Ann Haines

Graduate Program in Geography

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of the requirements for the degree of
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THE UNIVERSITY OF WESTERN ONTARIO
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Abstract

This thesis examines 20th century regime changes for the headwaters of the Bow (1911-2005) and Athabasca (1971-2005) Rivers. Changes in precipitation and temperature associated with the Pacific Decadal Oscillation dominate the Bow streamflow record. Higher snowfall, lower mean temperatures, and greater annual discharges occur during the "cool" PDO phase (1947-1976) with lower snowfall, higher mean temperatures, and lower annual discharges during the "warm" (1925-1946, 1977-2005) phases. Any long-term linear trends in the Bow record are masked by these multidecadal trends. The Athabasca record is too short to compare to the PDO but available data show patterns similar to the Bow. Differences in percentage glacier cover result in differences in median flow dates ranging from (June 29) on the Miette (0.2% glacier cover) to July 28 on the proglacial Sunwapta River (61% glacier cover). Additionally a visualization technique is developed which provides a complementary approach to evaluating low frequency regime changes.

Keywords

Streamflow, variability, southern Canadian Rockies, glacial cover, Pacific Decadal Oscillation (PDO), climate change, visualization, Bow River, Athabasca River

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Chapter 1

1 Introduction

1.1 Introduction

Alpine environments are highly sensitive to temperature changes and they respond to change more rapidly and earlier than lower altitude environments (Beniston, 2005, Rood *et al*, 2005). Models indicate that temperature increases due to global warming will be greater at higher elevations because a large portion of the available water storage is temperature sensitive (Stewart *et al*, 2005). High alpine glaciers and snow covered catchments are particularly sensitive to climate warming that can lead to greater snow and ice melt and pronounced changes in streamflow patterns (Munro, 2000, Moore *et al*., 2009). As 50% of the world's rivers have their sources located in mountain regions (Viviroli *et al*, 2002, Beniston, 2003) these changes will also influence adjacent lowland areas. Furthermore, water from glacier and snow melt is directly consumed by over 15% of the world's population as a freshwater source (Bales *et al*, 2006). The anticipated effects of temperature change are of particular importance in many alpine areas of western North America where streamflows are dominated by meltwater released during spring and summer (April – September; Watson & Luckman, 2006).

Climate changes are predicted to create variations in streamflow patterns in alpine environments (Stewart *et al,* 2005). Lemke *et al* (2007) indicated that, with a warming climate, glacier and snow-melt fed river runoff volume will increase initially with peak discharges occurring earlier in the spring. This phase would be followed by an overall decrease in runoff volume as less water becomes available from ice and snow storage (Demuth, *et al*, 2008). It has been suggested by Demuth *et al* (2008) that the period of increased discharge in some of the basins of the southern Canadian Cordillera has begun to enter this interval of decreased overall discharge. This analysis is based on a limited sample of two watersheds within the cordillera, thus it is important to examine other instrumental records from rivers in this region to see if such a prediction applies across a wider region.

It is also known that the glacial melt and snowmelt components of the hydrological system react differently to annual climate trends (Knowles *et al*, 2006). Several studies (e.g. Fleming & Clark, 2005, Stewart *et al*, 2005) have shown that glacial melt contribution to streamflow can cause unexpected modifications to discharge regimes and affect the timing and volumes of discharge. Thus it is important to attempt to understand these inputs and determine the difference between rivers with differing amounts of glacier and snow cover. This understanding could be undertaken by looking at records in the southern Canadian Cordillera where paired examples of adjacent rivers have varying amounts of glacier derived inputs. Analysis of proglacial records would also permit an understanding of how glaciers affect streamflow patterns and variability.

The natural variability of streamflow cannot be completely accounted for without analyzing the effects of atmospheric circulation patterns as they are known to provide regionally specific influences on both surface climate and streamflow trends (Moore & McKendry, 1996, Hamlet *et al.*, 2005). The Pacific Decadal Oscillation (PDO) has been shown to influence streamflow trends in western North America. Positive and negative regime shifts have been noted in 1925, 1947, and 1976 (Mantua & Hare, 2002 Stewart *et al.*, 2005). Hydrological records from the southern Canadian Cordillera frequently span the 1976 phase shift with some of the longer records recording the earlier two shifts so the effect of the PDO on streamflow in this region can be analyzed (St Jacques *et al*, 2010). Understanding the effect of these atmospheric oscillations is critical to evaluating patterns of variability and streamflow trends in this region (Watson & Luckman 2006, St. Jacques *et al*, 2010).

1.2 Scope of this Thesis

This study will evaluate the hydrological records of the headwaters of the Athabasca and Bow Rivers in the southern Canadian Cordillera. There has been no previous work on the Athabasca River which has several hydrological records of 40-50 years length and is an important contributor to the Mackenzie River. Previous work in the Rockies has examined the two adjacent basins to the south, the North Saskatchewan River (Demuth *et al.*, 2003, 2008, Comeau *et al.*, 2009, St. Jacques *et al.*, 2010) and Bow River (Hopkinson & Young, 1998). However, Hopkinson and Young (2008) only examined 42 years of the

Bow record at Banff beginning in 1951. As the full record is the longest continuous record of natural streamflow in the Canadian Rockies (1911-present) analysis of the full record provides a reference series against which the Athabasca and other basin's records may be assessed.

The upper Athabasca basin also has streamflow records for several tributaries that allow for the assessment of the control that differing amounts of glacial cover have on the hydrological regime of the system. The tributary Miette River near Jasper has minimal glacier cover whereas the gauge on the Sunwapta River at Athabasca Glacier has the longest (ca. 42 years) seasonal discharge record for a proglacial site in Canada. By analyzing these records evidence of trends related to glacial cover may be understood. Additionally, this investigation will examine the effects of the 1976 shift change of the PDO on the records from the Athabasca and Bow watersheds. The relationship between hydrological and precipitation changes will also be examined.

In addition to a more traditional statistical approach to hydrological analysis this study will also use an alternate technique of identifying trends in streamflow data using a novel visualization of streamflow data. Phal-Wostl (2007) suggests that as different audiences have different ways of absorbing scientific information, multiple (or different) ways of data presentation and analysis may be useful when data are needed for policy purposes (see e.g. Meko & Woodhouse, 2011). Sadie and Getz (2005) suggest that visually accessible information can make management and planning decisions easier. Therefore creating a visual interpretation technique to demonstrate trends in streamflow data may provide a useful tool for presenting data to policy makers. If successful, this technique could be applied to records from other areas of the southern Canadian Cordillera.

1.3 Structure of this Thesis

The body of this thesis will address these issues in four main chapters. Chapter 2 will provide a general review of previous work on hydrological studies in the western Americas and specific analysis of previous work in the Canadian Rockies will be highlighted. Chapter 3 will analyze selected records from the Athabasca and Bow Rivers, evaluating the seasonal discharge records and differing regimes of the Athabasca, Miette, Sunwapta, and Bow Rivers and the relative importance of glacier contributions. It will also assess the potential hydrological influence of the Pacific Decadal Oscillation. The relationships between precipitation and temperature changes and these hydrological records will be examined in Chapter 4. Chapter 5 will develop and detail a new visualization technique for analyzing hydrological trends in streamflow data based mainly on the longer Bow record. The final chapter will summarize the main findings with suggestions for future research.

Chapter 2

2 Studies of streamflow regime changes in the western North American Cordillera

2.1 Introduction

There have been many studies examining the relationships between mountain hydrology, glaciers and recent climate changes. After a brief overview of general studies, this chapter will examine previous major studies in western North America, concentrating on western Canada and specifically studies in the Canadian Rockies that address the natural variability of streamflow and its relationship to climate changes. It will also include a review of variation in streamflow trends due to different amounts of basin glacier cover and will discuss the influence of the Pacific Decadal Oscillation (PDO) on streamflow. Finally the results of more detailed research done in the southern Canadian Cordillera will be summarized.

2.2 General Studies

It is well documented that high alpine environments are sensitive to climatic changes and that they respond more rapidly to climate changes than lower altitude environments (Beniston, 2005). This makes them prime study areas for understanding the interaction between hydrology and climate. Also, water storage is temperature sensitive in alpine environments where streamflow is fed from glacial and snowmelt sources (Stewart *et al*, 2005). Munro (2000) points out that these sources of alpine water contributions are quite sensitive to climate warming causing changes to melt patterns and resulting streamflow trends. These effects can be seen both in the timing and volume of discharge in high alpine areas (Stewart *et al*, 2005). The research summary in the 2007 IPCC report (Lemke *et al*, 2007) indicated that, with a warming climate, the volume of river runoff fed from glacial or snowmelt regimes would initially increase with peak discharges being observed earlier in the spring. Subsequently runoff volumes would decrease as less water becomes available from ice and snow storage to feed the system (Demuth *et al*, 2008, Marshall *et al*, 2011). Studies of the natural variability of streamflow in these basins are critical to understand these changes (Watson & Luckman, 2006). However, relatively little work has been carried out on natural flow controls in high elevation areas due to the difficulty in accessing these remote areas and a general lack of available streamflow records from high altitude sites (Viviroli *et al*, 2002, Bales *et al*, 2006). Nevertheless it is important to examine those instrumental records that do exist to determine whether these predicted changes can be detected. One area where such a study can feasibly be undertaken is in the southern Canadian Cordillera as there are several watersheds that meet the criteria for such analyses.

Glaciers and alpine snowpacks provide a critical long-term hydrological control by storing water during cool and wet periods and releasing it during warm and dry periods (Rood *et al*, 2005, Masiokas *et al*, 2006, Demuth *et al.*, 2008, Sauchyn *et al*, 2009). Warming climate can cause modification to this natural control on water storage that will change alpine streamflow regimes. Recent climate warming is resulting in rapid glacier loss (e.g. Bolch *et al*, 2010) potentially causing a shift from glacial melt-dominated to snowmelt -dominated regimes in many mountain environments (Huss *et al*, 2008) and also changes in snowmelt dominated regimes (Stewart *et al*, 2005) .This is critical as these two components of the hydrological system respond differently to annual climate trends (Knowles *et al*, 2006). A shift in the balance between rain and snowfall can cause changes in discharge timing that could be critical to downstream water needs (Knowles *et al*, 2006). It is therefore important to understand all components of this hydrological system so that the effects of these changes can be documented and understood.

2.3 Studies in the western Cordillera of North America

In recent years several studies have reviewed hydrological changes in the western American Cordillera between Alaska and Mexico. The most important studies are Dettinger *et al*, 2004, Stewart *et al*, 2004, 2005, Rood *et al*, 2005, Hamlet *et al*, 2005, 2007, and Bales *et al*, 2006. Dettinger *et al* (2004) studied the possible effects of climate change on three snowmelt-dominated mountain basins in the Sierra Nevada region of California where human discharge modification had been kept to a minimum. They used Parallel Climate Models (PCM's) and historical data to simulate the hydrologic response to climate variation related to historic greenhouse gas concentrations over the 20th century and predicted concentrations for the 21st century. The PCM's demonstrated that streamflow timing is highly influenced by cool season warming that changes the rain-to-snow mix in precipitation. Over the historic period of study snowmelt was seen to be occurring earlier in the year, causing decreased discharge in late summer and autumn. Decreases in snowmelt amounts were prevalent in records from the second half of the 20th century.

In the first large scale study Stewart *et al* (2004) examined hydrological data throughout the cordillera from Alaska to Mexico based on 279 high quality, daily or monthly natural discharge records from 1948-2000. Although several Canadian rivers were included, with some from the Rockies, specific details of these gauge records are not given in the paper. Most runoff in these rivers (50-80%) was derived from spring and summer snowmelt. This study focused on changes in the timing of runoff based on the initial melt pulse, changes in monthly discharge distribution and the date of the centre of mass of annual flow (CT)[1]. CT date was calculated using average monthly data in this paper but the authors noted this calculation could also be applied to daily flow data. CT data were used as they were easily calculated, insensitive to interannual variation (in relation to other measures) and comparable across basins. This measure has been used by these authors in subsequent studies of streamflow since this paper's publication (e.g. Stewart *et al*, 2005). Their analysis showed that in general the CT date was trending to occur earlier in the year at most stations including all of those within the southern Canadian Cordillera. The earlier CT trends were also found to correlate well with regions experiencing temperature warming. The areas demonstrating the widest ranging changes in CT date were found to be in rivers of the continental United States and southern Canada that had strong snowmelt dominated regimes and showed CT trends occurring between 5 to 15 days earlier. The northernmost rivers in the Cordillera and those at high elevation showed lower sensitivity to change and many had CT changes of < 5 days. This was attributed to colder temperatures in these areas reducing the impact of

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[1] CT date is calculated based on the water year and is not the same measure as median flow date.

small temperature increases that would have little effect on the duration of the snowmelt period since the average values would continue to remain below freezing. It was also noted that the timing trends observed in this study showed consistent changes in the rate and amount of change across western North America.

In their subsequent paper Stewart *et al* utilized daily data from the US stations (monthly data from the Canadian rivers) from the same network plus some additional stations for a more refined analysis[2]. In total 294 snowmelt dominated and 91 non-snowmelt dominated records from the 1948-2000 period were used including 53 snowmelt dominated Canada stations. Linear trend analysis was performed on April through July (AMJJ) fractional flow, spring pulse onset date, and CT date. It was in this work that the CT calculation for daily data was described in detail. Both spring pulse onset and CT date showed trends towards earlier dates for the snowmelt dominated basins. The CT timing was 10-30 days earlier over the 50 year study period for the snowmelt dominated basins and 5-25 later for the non-snowmelt dominated basins. The fraction of AMJJ streamflow was 50-80% for snowmelt and 30% for non-snowmelt dominated basins.

Recent patterns of snowmelt for basins in the western Cordillera were examined in a series of papers by Mote *et al*, 2005 and Hamlet *et al* 2005, 2007. These studies used April 1st Snow Water Equivalent (SWE) data from the western United States and southern British Columbia using SNOTEL snowcourse measurements. The April 1st date is the most common observation date for both monthly and daily records and is commonly used for hydrological forecasts. Most study sites in the Mote *et al* (2005) analysis reached peak SWE around this date. Mote *et al* (2005) developed a physically-based variable infiltration capacity (VIC) model using minimum and maximum temperatures and precipitation data to create snowpack time series. This model is well validated in hydrological studies to capture climate sensitivities (Hamlet & Lettenmaier, 1999, Hamlet *et al*, 2005). Mote *et al* (2005) used SNOTEL snowpack data from 1144 stations from the 1950-1997 period (824 with complete records) to model snowpack over

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[2] They do not indicate whether these additional stations were in the US or Canada.

several time periods between 1915 and 2002. These simulations showed that the largest decrease in April 1st SWE values occurs at lower elevations due to warmer midwinter temperatures that are more susceptible to climate warming. They also noted a widespread decrease in SWE in the second half of the 20th century due to climate warming, corresponding to snowmelt observations by Dettinger *et al* (2004).

Hamlet *et al* (2005) used the same SWE sites and 1950-1997 data to create a VIC model from 1915-2003. Their model was run on three different scenarios using; (1) a base run with daily temperature and precipitation values: (2) a fixed precipitation levels and variable temperatures, and (3) fixed temperatures with variable precipitation. Based on these model results Hamlet *et al* (2005) concluded that increased winter runoff, earlier peak streamflow, and decreased summer streamflow volume were related to increased winter and spring temperatures, accompanied by a widespread decrease in SWE across the western US states and south-western Canada. Shorter term decadal scale variations in SWE were related to precipitation variability (see discussion of PDO below).

In a more comprehensive analysis Hamlet *et al* (2007) developed a VIC model to analyze runoff, evapotranspiration (ET) and soil moisture. They found all three variables showed earlier mean event dates over the 1916-2003 period. The earlier mean runoff timing was related to temperature trends and matched the changes in snowmelt timing discussed in Hamlet *et al* (2005). The region studied by Hamlet *et al* (2007) has a large snow accumulation season and changes in spring melt regime led to changes in discharge during the entire record including decreased mid-late summer streamflows. Hamlet *et al* (2007) noted that colder areas (e.g. the Canadian sites) had runoff peaks in May and June whereas discharge in the coastal regions of the PNW peaked in March and April. Nevertheless all regions demonstrated an earlier trend in runoff timing with the greatest change in areas where mid-winter temperatures were in the -10 to -5°C range. Hamlet *et al* (2007) also found that changes in autumn and winter streamflows were more influenced by changes in precipitation patterns.

Rood *et al* (2005) examined trends in annual discharge records for the longest and least regulated rivers in the 'Hydrographic Apex of North America' i.e. the western North

American cordillera. Thirty-one high upstream gauges were studied plus four downstream reaches with long records and some flow control. Most records began in the early 1900's but when data was missing, data from proximal active and discontinued gauges were spliced together when there was a period of overlap or the gauge had been moved. However there were only eight long, fully continuous records namely: North Saskatchewan River at Edmonton, Bow River at Banff , Belly River near Mountain View, Fraser River at Hope in Canada and the St. Mary River near Babb, Snake River near Moran, Columbia River at the Dalles and Missouri River at Fort Benton in the USA. Many others lacked data during the 1930's and 40's. Many sites also lacked winter data and small sections of missing data were interpolated based on the values from previous years or adjacent stations to the missing entry. The majority of records (21 of 31) showed a decreasing trend and half (15) were significant at the 0.1 probability level. No rivers showed significant increases in discharge. Most of the Canadian records showed significant decreases (16 of 21, 14 at the 1% level). The six records of rivers flowing east from the Rockies all showed strongly significant decreasing trends though the 20th century (Smoky River at Watino, Athabasca River near Jasper, North Saskatchewan River at Edmonton, Red Deer River at Red Deer, Bow River at Banff and Calgary). Most early records show low streamflows in the 1920's and 30's with an increased discharge thereafter. However these changes are less well marked in the Bow record from Banff and Rood *et al* (2005) suggest this reflects increased glacier melt offsetting the decreases in precipitation.

Stahl and Moore (2006) examined the contribution of glaciers to late summer streamflows from a sample of 236 hydrometric stations in British Columbia (BC) that had a minimum of 10 years data during the 20th century by comparing mean August discharges from 113 glacierized and 123 non-glacierized catchments. They analyzed sites on a regional basis and found that for catchments with glacial cover the regional patterns were statistically significant. Negative streamflow trends were common in glacial catchments across most of BC except for some sites in the northern region of the province (Moore & McKendry, 1996 also noted differences between northern and southern study sites in BC). No significant regional trends were found for the non-glacierized group and Stahl and Moore (2006, p4) partially attributed this to their "'patchy' sampling in both space and time" (some of these records are only 10 years long). The authors conclude their work by encouraging more site-specific studies.

Moore *et al* (2009) examined the influence of glacier changes on streamflow variation with examples from the continental United States, western Canada, and Alaska. They note that although glaciers affect streamflow at various timescales, the strongest effects are the augmentation of summer and autumn streamflows. This is seen most clearly in August during hot and dry years with little snow accumulation. They found that the streamflows are sensitive to melt inputs in catchments with as little as 2-3% of glacial cover. Fleming and Clarke (2005) examined rivers in the southwest Yukon and northwest BC and show that during a recent warm period annual discharge volumes decreased in the non-glacierized catchments and increased in the glacierized areas due to the effect of glacial meltwater. However, Moore *et al* (2009) also note that while initial temperature increases can result in higher streamflow, if temperatures continue to increase the continued loss of ice will result in decreasing discharge over time. Moore *et al* (2009) also suggest that, based on Fleming and Clarkes results, the glaciered catchments in SW Yukon and NW BC are in the first stage of increased annual discharge. Moore *et al* (2009) stress that streamflow predictions in such catchments must account for these glacier related-effects unlike the earlier predictions for the Lillooet River by Moore (1992) and Loukas *et al*, (2002).

2.4 The relationship between the Pacific Decadal Oscillation and streamflow in western North America

The PDO is the leading principal component of North Pacific monthly sea surface temperature (SST) variability (Mantua *et al*., 1997, Rodinov & Assel, 2001, Hidalgo & Dracup, 2003, MacDonald & Case, 2005) with an event persistence of 20-30 years (Mantua & Hare, 2002). The PDO has been recognized as a major influence on climate the Pacific Northwest, and particularly on precipitation. This atmospheric oscillation is known to shift between positive and negative phases and regime shifts have been identified in 1925, 1947, and 1976 during the 20th century (Mantua *et al*, 1997, Zhang *et al*, 1997). The influence of the PDO on streamflow and precipitation has been recognized in many papers e.g. Moore and McKendry (1996), Hamlet *et al*. (2005), Stewart *et al*,

(2005) and Gobena and Gan (2006). These effects are most prominent in winter months (Moore *et al*, 2009) and in western North America have been linked to variations in winter precipitation, wintertime air temperature, snowpack, and glacial mass balance records (Mantua *et al*, 1997, Selkowitz *et al*, 2002, Munro, 2005, Watson & Luckman, 2005a, Mote, 2006, Watson & Luckman, 2006, Demuth *et al*, 2008, Moore *et al*, 2009). However, while winter may be the most impacted season, the PDO's effect on streamflow is seen most strongly in annual discharge values; positive phase PDO years show lower annual discharge with higher annual discharge occurring in negative phase years (Mantua *et al*, 1997). The mechanisms controlling the PDO remain unknown and have been difficult to model. However, the phenomenon appears to have intensified during the 20th century and become more important in driving hydroclimate trends (Gedalof *et al*, 2002, Mantua & Hare, 2002, Moore *et al*, 2002, MacDonald & Case, 2005). Therefore locating the influence of the PDO in streamflow records has become more widespread as it is important to determine or isolate the influence of the PDO before extrapolating trends from hydroclimate records (St Jacques *et al*, 2010).

Stewart *et al* (2005) recognized the potential influence of the PDO as the 1976 "shift" occurs in the middle of their 1948-2000 data set, the first half being in the 1947-1976 "cool phase" and the latter half in the "warm phase" from 1977-2000. They concluded that the PDO did contribute to some of the changes in their CT data but in some cases it could not be separated from the warming trends. However, they noted that the PDO had the greatest effects on streamflow in their Pacific Northwest region, which includes southern Canada, compared to the southwestern US stations. Hamlet *et al* (2005) looked at the two full cycle PDO regime periods of 1925-1976 (warm through to cold phases) and 1947-2003 ("cool" through to "warm" phase) while analyzing SWE values from SNOTEL sites. They linked trends in SWE to precipitation changes based on the PDO phases: the 1925-1976 cycle shows an overall increasing SWE trend reflecting drought conditions in the "warm" phase moving into wetter conditions in the "cool" phase and 1947-2003 shows the reverse, a decreasing SWE trend matching the decrease in precipitation in the colder regions of the PNW (which includes the southern Canadian Cordillera). No temperature effects were found related to the PDO phase as the VIC models all demonstrated an overall decrease in temperature over time that was not related to the PDO changes. Hamlet *et al* (2007) matched the 1947-2003 PDO cycle VIC streamflow models to the streamflow trends observed in the work by Stewart *et al* (2005).

Rood *et al* (2005) examined the relationship between five-year means of their hydrological data and the PDO over the 20th century and found a significant correlation. They note a stronger correlation for the latter half of the 20th century but caution that longer records would be needed to make a definitive statement. They also note that this change in phase and accumulation is based on the glacier cover in the catchment. The glacierized Mendenhall River catchment showed an increase in streamflow over all seasons during the "warm" phase with increased rain flowing off the glacier in winter and increased melt-based streamflow occurring in the summer months. Similar observations of glacial melt influencing streamflow have been reported by several other studies, e.g. at Place and Peyto Glaciers, in Canada (Munro, 2005, Watson *et al*, 2006, Demuth *et al*, 2008).

Another work that touches briefly on the effect of the PDO is that by Stahl and Moore (2006). Along with analyzing all the records from the 20th century in BC the researchers also looked at only those records that existed since the 1976 phase shift and contained data for all years from 1976-1996 which gave them a sample size of 143 hydrometric stations. The purpose of this analysis was to see if there was a consistent regional pattern observable within the PDO phase across BC. These stations generally show negative streamflow trends over this 20 year period. These trends along with the spatial difference seen between northern and southern BC are consistent with linkages that have been made to the PDO by Moore and McKendry (1996) and Moore *et al* (2009).

Although the distinct 1976 regime shift from "cool" to "warm" PDO phases can create problems in the linear analysis trends in hydrological data in the late 20th century there have been few attempts to isolate its effects on these trends. Recently St. Jacques *et al* (2010) examined records from 14 rivers flowing eastwards from the Rockies in Alberta plus two in Northern Montana to investigate the influence of the PDO in these records. They selected continuous HYDAT records that span at least one full cycle of the PDO (i.e. ca. 1950's-2000) and generated mean annual flows for each year of the record. Half

(8) of these rivers were described as having naturalized flow records and half had records with data that had been estimated and/or compensated for human impacts. Surprisingly the Bow River at Banff was not included in this analysis but the modified record for the Bow at Calgary was used. The eight records that required “naturalization” were located outside the mountainous areas. St. Jacques *et al* (2010) concluded that water supply was decreasing even when the PDO and other sources of natural variability were factored out: 10 of 16 stations showed significant decreases with only one indicating a significant increase in discharge between 1903 and 2007. They also note that rivers within the Bow watershed and the North Saskatchewan basin were more likely to show decreasing streamflows than surrounding watersheds. The overall decreasing trend (after removal of PDO influence) was attributed to increasing temperatures and/or human impact. They confirm the PDO’s strong influence on Alberta streamflows with higher discharges during the cold phases and lower discharges during the “warm” phases. St. Jacques *et al* (2010) also note that the discharge records for southern Alberta are already indicating that future water availability is decreasing and that greater water supply is needed to meet future demands.

The above overview covers more general papers that examine recent hydrological change in western Canada and their relation to the PDO. The next section will include a more detailed examination of studies that have focused on hydrological conditions in the southern Canadian Cordillera.

2.5 Studies in the Canadian Rockies

Few studies have examined changes in the hydrological regimes of the southern Canadian Cordillera and most of those discussions only include a few Canadian stations within broader regional studies (e.g. Mote *et al*, 2005, Rood *et al*, 2005). Only two studies focus on specific headwater basins in the Rockies that are discussed in detail below.

The Bow River at Banff is the longest continuous, high elevation record of unregulated streamflow in the Canadian Cordillera. Hopkinson and Young (1998) examined the relationship between streamflow and glacier wastage based on the daily discharge record from 1951-1993. They based their information on glacier mass balance (GMB) records from Peyto Glacier that is immediately north of the basin and shares the hydrological divide with Bow Glacier which is the source of the Bow River. Young had previously worked on the partitioning of discharge from Peyto Glacier between glacier melt and other sources using the record obtained during the International Hydrological Decade (1965-78, Young, 1981). In his 1977 paper Young had determined that the Peyto mass balance record was representative of glacial conditions in the adjacent Upper Bow watershed with similar climate and topographic conditions. Hopkinson and Young determined changes in ice cover for the Waputik Icefield (source of both Bow and Peyto Glaciers) based on aerial photography taken in 1951 and 1993. Mean daily discharge for the Bow was aggregated into annual volumetric totals and compared with glacial wastage determined from several upstream glacial sites. They observed that the years 1970, 79, 83, 85, 87, 88, and 93 with below average river basin yields coincided with years of high glacial wastage whereas above average river basin yields occurred in periods with no glacier wastage and, in some cases small net glacial storage, such as in 1954, 59, 66, and 76. The lowest and highest yield years of 1970 and 1954 corresponded to the highest wastage (loss of $122.9*10^6$ m^3) and storage years (gain of $61.4*10^6$ m^3) respectively. Hopkinson and Young (1998) considered these extremes reflected increased winter precipitation and reduced summer temperatures during 1954 and lower winter precipitation levels during 1970. They suggested that small glaciers can generally regulate streamflow , as in 1970, but not all low yield years are augmented by glacial melt as seen in 1957 (See Figures 6 and 8 in Hopkinson & Young, 1998). High streamflow may result from increased precipitation and/or increased glacier melt during summers with higher than average temperatures. These observations led Hopkinson and Young (1998) to conclude that the interrelationships between climate, glaciers, and streamflow are more complex and other basin sources may contribute to the regulation of streamflow. They also suggested that lower summer streamflows will result from future glacier wastage in the Bow Valley with increased potential for higher spring runoff and lower summer streamflows, resulting in increasing water shortages throughout the catchment. Surprisingly there is little discussion of the streamflow variability over the full length of long hydrological record.

The Peyto mass balance record was also the focus of the other major Canadian study of the upper North Saskatchewan basin (Demuth & Pietroniro, 2003). The North Saskatchewan headwaters lie between the Upper Bow Watershed and Upper Athabasca Watershed, including some drainage from the Columbia Icefield. Peyto Glacier has the longest glacier mass balance record in Canada (1966-present, Demuth & Keller, 2006) and the glacier stream was gauged from 1966-76. Five headwater streamflow gauge records from the upper North Saskatchewan basin have mean, minimum and maximum daily discharge data available within the 1950 to 1998 period however, none of these station's records are continuous and complete. These five records are North Saskatchewan River at Saskatchewan Crossing, Siffleur River near the Mouth, North Ram River at Forestry Road, North Saskatchewan River at Whirlpool Point, and Mistaya River near Saskatchewan Crossing that have continuous records for 20, 22, 24, 29, and 49 years respectively. Peyto Creek from the glacier drains into the Mistaya River which is a major tributary joining the North Saskatchewan at Saskatchewan Crossing. Although the streamflow records for the basin are fragmentary Demuth and Pietroniro (2003) felt they provided the best opportunity to determine the effect of climate change on glaciers and their contributions to water supply.

Only the longest record from the Mistaya River was used for statistical analysis of streamflow trends in this basin, it has a 12% glacier cover contribution. The data were analyzed at an annual scale and also for the 'Transition-to-Baseflow' (TBF) period of August 1 – October 31. Demuth and Pietroniro (2003) consider that streamflow has become more variable in glacierized portions of the upper North Saskatchewan River basin since the middle of the 20th century as a result of deceasing glacier cover in these high alpine environments as the timing and discharge volumes in this basin are greatly influenced by glacier-derived meltwater. Statistically significant decreases were observed for mean and minimum discharge values of the Mistaya over the period of record. However, there was a minor but not significant increase in maximum discharge which was attributed to the reduction in glacier firn within the catchment as this reduces the lag time between surface melt and discharge to the river. Non-parametric tests were run on the four shorter gauge records but, with the low sample depth, the only significant results were for decreasing trends in minimum discharge at three of these gauges.

There are no high elevation climate stations within the North Saskatchewan basin. Demuth and Pietroniro (2003) found the strongest correlations with the Banff climate record. However, they found no correlation between minimum and maximum streamflows and Banff climate data. Nevertheless, the mean TBF flow had a 0.37 correlation value with autumn temperature but no relationship to precipitation values. Winter mass balance (WMB) records for Peyto were more strongly correlated to the mean TBF flows – r= 0.53 (significant at the 95% confidence level) between TBF and WMB and r= 0.34 (significant at the 90% confidence level) for annual GMB. Demuth and Pietroniro (2003) indicate the need to examine these glacier-hydro-meteorological relationships further. They also noted the strong influence of the PDO on inter-decadal changes in winter precipitation, winter glacier balance and streamflow, based largely on the Peyto GMB record. However, no statistical analyses were undertaken to compare the PDO to these data.

More recently Comeau *et al* (2009) modeled the contribution of glaciers to streamflow in the headwaters of the North and South Saskatchewan Rivers using WATFLOOD/SPL9 (Kouwen, 1988). They utilized hydrological data for annual and July-September periods from 11 headwater basins in combination with Landsat-derived glacierized area maps from 1975 and 1998. Modeled runs of WATFLOOD were carried out for the 1970-1980 and 1993-2003 periods and verified in part by hydrological analysis from HYDAT data for nine glacierized and non-glacierized basins in this study area. The glacier contribution to flow was modeled as ‘melt’- equivalent to the SWE volume accumulated on the glacier in a given hydrological year - and ‘wastage’- the flow volume that exceeds that SWE volume and represents the annual net loss of volume on the glacier. The only other Canadian study that attempts to estimate the volume loss from glacial ice is Young’s (1981) melt and wastage estimates derived from the 1967-1977 glacial mass balance record from Peyto Glacier (Young, 1981) and Peyto Creek streamflow data for the same period. These data were scaled to match glacier volumes changes for the North and South Saskatchewan River headwaters between 1975 and 1998 using a regionalized volume-area scaling technique (Bahr *et al*, 1997). Comeau *et al* (2009) note however, the data limitations for this study and the dearth of studies from comparable basins.

Comeau *et al* (2009) report that in sub-basins with greater than 10% glacier cover, ice and snow contributed 73-84% of July – September streamflow with more than 60% of the ice and snow contribution coming from ‘melt’. The ice and snow contributions from basins with 1-10% glacier cover were 26-75% and basins <1% glacier cover had a maximum of 10% melt derived July-September flow. The model estimates for the Bow River at Banff were 3.4% glacier cover and 58% contribution to the July-September 1975 flow which decreased to 2.2% glacier cover and 41% July-September streamflow in 1998. Comeau *et al* (2009) conclude that the relative percentage contribution made from glacier loss increases with glacierized area in the basin and that the melt of snowpack from the basin is a far larger contribution to streamflow than glacier melt. The authors note this was a first attempt to model the ‘melt’ and ‘wastage’ components to streamflow but that ‘wastage’ from specific glaciers would vary based on regional topographic and climatic attributes that were not accounted for in this model. Their research into the effects of glacier melt demonstrated that the major impact of glacier loss on streamflow will be changes in the timing of streamflow events with an earlier hydrological peak and reduced late season glacier contributions. In the long term annual discharge volumes will decrease as glacier wastage contributions decrease due to loss of glacier cover.

2.6 Summary

Several studies in North America show changes in the hydrological regime of high alpine catchments and indicate the potential effects of both recent warming and changes in circulation on streamflow regimes. The largest observed change is earlier timing of discharge (both seen in peak discharges and CT dates) which is especially prominent in areas experiencing temperature warming. There is also an overall decrease being observed in streamflow volume throughout western North America. The effect of glacier cover is very prominent with glacierized and non-glacierized catchments behaving in different ways. Generally increases in streamflow due to glacial melt are observed but in some cases discharges are beginning to decrease due to lesser ice cover being available to sustain streamflow. As well the Pacific Decadal Oscillation is seen to be having an effect on hydrological trends especially in relation to the twentieth century regime shifts. Overall though it must be concluded that hydrology, climate, and glacial effects are found to be highly interrelated. However, the literature on hydrological variability in the southern Canadian Cordillera is sparse and, in view of the importance of this water resource more research is needed. Therefore the primary aim of the following research is to examine streamflow variability in the headwaters of the Athabasca and Bow watersheds that have not previously been studied in detail.

Chapter 3

3 Twentieth century changes in streamflow in the Bow and Athabasca headwaters

3.1 Introduction

The previous chapter has summarized the published literature on recent changes in streamflow in the western Cordillera of North America noting that the Canadian coverage is sparse, particularly in Alberta. The Athabasca, North Saskatchewan and Bow Rivers are major headwater sources for drainage from the central Canadian Rockies but have received little detailed study. The North Saskatchewan has been studied in some detail by Demuth and Pietroniro (2003) whilst less than half the length of the Bow record has been examined (Hopkinson & Young, 1998) and no studies have been carried out in the Athabasca watershed. This chapter will review the streamflow records for the Bow River at Banff, the Athabasca River near Jasper and two Athabasca tributaries. The specific objectives are (1) to compare and document hydrologic variability in these two basins and evaluate changes during the 20th century, (2) to examine possible differences in the response of high elevation basins with variable amounts of glacier cover, and (3) to determine, where possible, the relationship of changes in streamflow to variations in the Pacific Decadal Oscillation (PDO).

3.2 Study Area and Methods

The Upper Bow and the Upper Athabasca watersheds (Figure 3.1) flank the North Saskatchewan drainage basin and are located entirely within Banff and Jasper National Parks, east of the Continental Divide. These basins are alpine environments with headwaters in the Columbia (Athabasca) and Wapta (Bow) Icefields. They contain a range of icefield, alpine tundra, and subalpine forest ecozones dominated by coniferous forest (Scott, 1995). The two basins have similar altitudinal ranges, ca. 1050 to 3750m for the Athabasca and 1200m to 3400m for the Bow. Both rivers are unregulated, though there are several large lakes in the Bow catchment, and the gauge records are considered representative of natural streamflow regimes within the Cordillera.

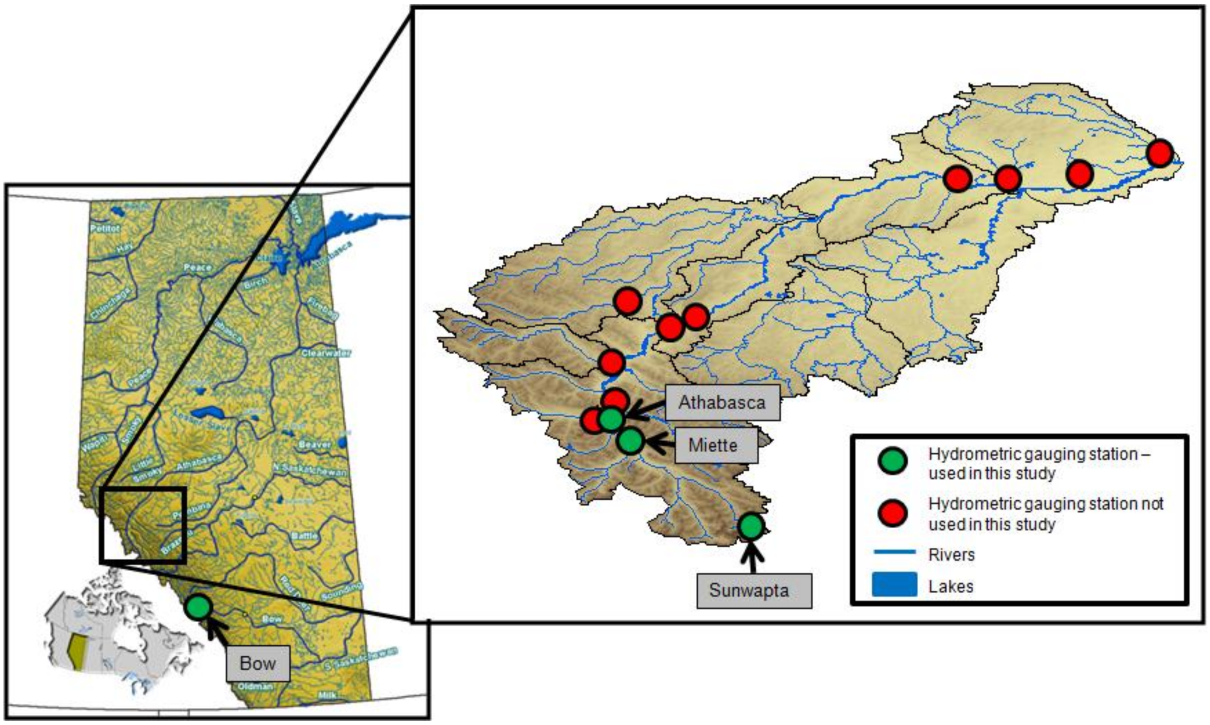

Figure 3.1: Hydrometric gauging sites available in the Upper Athabasca Watershed. The gauges of interest in this study have been labeled.

Table 3.1: Location, basin size, and length of hydrological records used in this study.

ID No.	*Station Name*	*Avg. Mean Annual Flow (m^3/s)**	*Lat. N*	*Long. W*	*Station Elevation (m)*	*Area Drained (km^2)*	*Full Year*	*Seasonal*
05BB001	Bow River at Banff	39.31	51 10	115 34	1402	2210.0	1911-2005	1909-1910
07AA001	Miette River near Jasper	10.57	52 51	118 06	1041	628.5	1915-1920, 1976-2005	1914, 1974-1975
07AA002	Athabasca River near Jasper	87.29	52 54	118 03	1041	3872.7	1914-1921, 1924, 1926-1930, 1971-2005	1922-1923, 1925, 1970
07AA004	Maligne River near Jasper	16.16	52 55	118 01	1070	908.0	1973-1997	1916-1918
07AA007	Sunwapta River at Athabasca Glacier	3.34	52 12	117 13	1945	29.3	-	1952-1954, 1956-1958, 1960-1963, 1965-1968, 1970-1996
07AD001	Athabasca River at Entrance	187.26	53 22	117 41	976	9530.0	1916-1920, 1924-1939, 1956-1960	1915, 1921-1923, 1955, 1961
07AD002	Athabasca River at Hinton	172.42	53 25	117 34	963	9764.8	1962-2005	1961

* Mean Daily Discharge values are based on full year data only except for Sunwapta where only June 1- September 30 data are available

3.2.1 Available gauge records

The daily hydrological records used for this study are from the Water Survey of Canada's (WSC) 2007 archived hydrometric database (HYDAT 2007). The stream gauge on the Bow River at Banff (Table 3.1, Figure 3.1) has the longest, continuous, high elevation unregulated streamflow record in the Canadian Cordillera (Hopkinson & Young, 1998), extending from 1909 to the present. It monitors an area of 2210 km^2 and, although there are shorter records available for an upstream station at Lake Louise, the length and continuity of the Banff record make it the primary target for analysis. Hopkinson and Young (1998) carried out a limited assessment of annual streamflow volumes for the 1951-1993 period. The hydrological records for the Athabasca headwaters are shorter and more fragmentary and have not been analyzed previously. The Bow River at Banff as well as the available gauge records for the Athabasca with a minimum of 25 consecutive years are shown in Table 3.1 and Figure 3.2. Following early recording periods in the 1910s and 1920s, many gauges were discontinued and monitoring was not resumed until the 1970s. In addition several rivers are only gauged seasonally (usually

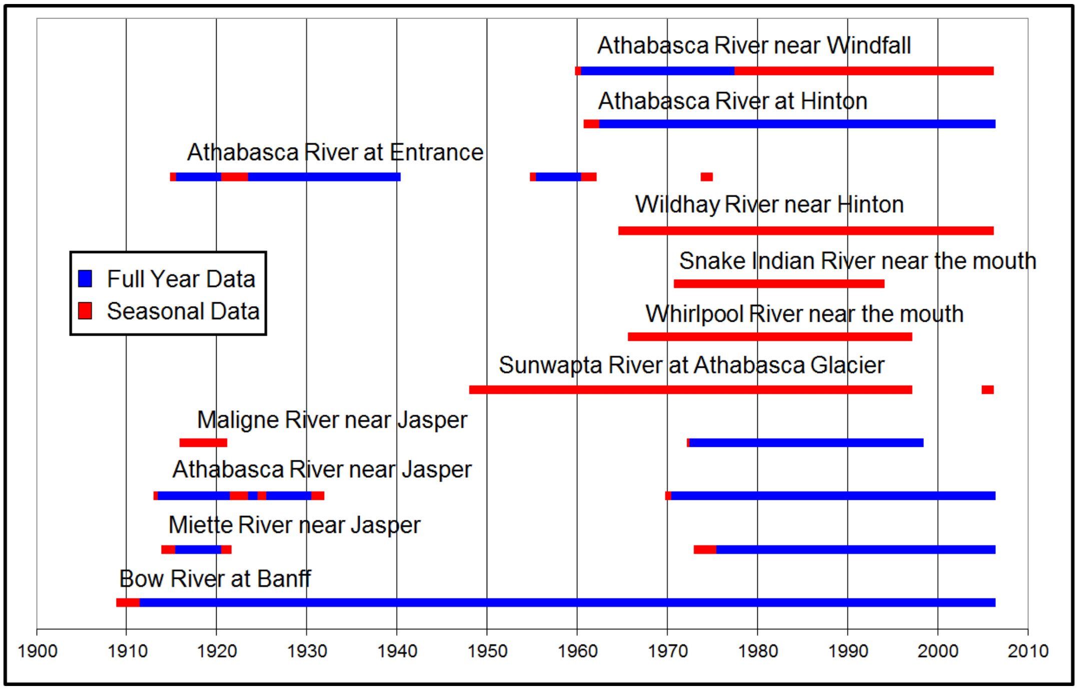

Figure 3.2: Gauge records for the Bow River at Banff and gauges in the Upper Athabasca Watershed that contain >20 years of data.

April – October). The Athabasca near Jasper was selected as the primary station of interest as it contains sporadic records from the 1914-1930 period and a continuous record from 1971-2005. Although the record from Hinton is longer, especially if it could be combined with the Entrance record upstream, the drainage area to these gauges is much larger and includes considerable discharge from tributaries in the Front Ranges and Foothills downstream of Jasper, areas with relatively little glacier cover and of lower elevation. Therefore the Jasper record is more comparable with the Bow record. Moreover, the Jasper gauge is only a short distance downstream of the confluence with the Miette River near Jasper. These two basins have relatively similar physiography but marked differences in glacier cover, ca. 7% (Athabasca) and 0.2% (Miette, Dr Roger Wheate, pers. comm.) As no tributaries enter the Athabasca in the short distance between the Miette Junction and the Athabasca gauge, the contribution of the two basins can be separated by simple subtraction.

The Sunwapta River is one of the main headwater tributaries of the Athabasca River and has been gauged seasonally for almost 50 years at the outlet of the small proglacial lake in front of the Athabasca Glacier. The lake basin presently has ca. 61%[3] glacier cover and the gauge was only ca. 0.2 (1950s) to 1km (presently) from the glacier toe. Although the record is only seasonal (May – October) and at times incomplete, it is the longest discharge record for a pro-glacial river in Canada. The records from the Athabasca, Miette and Sunwapta rivers in the Athabasca headwaters are of comparable or greater length than those records used by Demuth and Pietroniro in their 2003 study of the North Saskatchewan River. In addition, the complete Bow record provides a regional reference record that covers most of the last century.

The HYDAT gauge records are classified in this study as having ‘full year data’ where streamflow values listed in the WSC record are available for all 365 days of the Julian year. WSC streamflow estimates included in the HYDAT records are not counted as missing data in this study. Full year data for the CT analyses utilize those years with 365

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[3] The area of glacier cover was determined from the 1;50,000 NTS sheet 83/C , Columbia Icefield, printed in 1969 based on 1955 and 1956 aerial photography.

days of data between October 1st and September 30th (the hydrological year). Records classified as 'seasonal data' have daily data from June 1st to September 30th. WSC estimates short periods of missing data in these records using their own procedures and calculations (Water Survey of Canada, 2001) and also adjusts records to compensate for relocation of gauges or changes in recording method (e.g. manual to instrumental). Although it would be possible to improve the completeness of some records by replacing short periods of missing data remaining in these archived records, this would necessitate using different interpolation techniques and, as these data gaps did not meet the WSC criteria for replacement, further changes were considered unwarranted. Using the interpolation techniques outlined in Rood *et al* (2005) could only add a maximum of six years to the Athabasca River record and two years to the Bow record. Based on the requirements that data need be present in the years prior and subsequent to the missing data an attempt to extend the record or the 'seasonal' period for the Sunwapta River is not possible. All analyses were performed using daily instrumental streamflow data in order to determine changes at the highest resolution possible.

Microsoft EXCEL software was used to derive mean annual flow, date and volume of peak daily discharge, mean monthly and total discharge, seasonality of discharge, and date of centre timing of mass of annual flow (CT) from the daily HYDAT data. The technique used to determine CT is that developed in Stewart *et al*, 2005. It is calculated using their formula

Equation 3-1: Center of mass of annual flow (CT) date

$$CT = \sum(t_i q_i)/\sum q_i$$

where t_i is the number of days since the beginning of the water year (day 1= October 1) and q_i represents the discharge value of the water year at day i. These analyses were carried out for 'full water year' (October 1st to September 30th) and 'seasonal' (June 1st to September 30th) windows depending on data availability. The following analyses will firstly compare the Bow and Athabasca drainages before examining the sub-basins within the Athabasca drainage. Finally the analyses will examine the possible effects of the amount of glacier cover and influence of the PDO on discharge in these systems.

3.3 Comparison of the Bow and Athabasca Rivers

The Bow River at Banff gauge record begins in 1909 although 'full year data' are not available until 1911and are continuous until 2005. It provides a comprehensive record of hydrologic change during the 20th century and provides a benchmark against which other records can be compared. The record from the Upper Athabasca watershed is shorter and more fragmented; the gauge at Jasper is at the Maligne Bridge and operated from 1913-1931 and 1970-2005. It has full Julian year data for 1914-1921, 1924, 1926-1930, and 1971-2005. Comparison of this discontinuous record with that at Banff may provide context for the analysis of changes in the Athabasca record as both rivers drain similar high alpine environments. The Athabasca basin is larger, has a greater glacier cover and greater water yield per unit area (Table 3.2). Approximately 80% of discharge in both rivers occurs between May and October with the largest amount (ca. 65%) in June, July, and August although the Bow has a greater percentage of discharge in June, whereas the Athabasca has relatively greater discharge in July and August. Over the 1971-2005 interval the date of the 50th percentile of flow for Jasper (July 18th) is 11 days later than Banff (July 7th, Figure 3.3) but the annual hydrographs and flow accumulation curves are similar (Figure 3.4).

Table 3.2: Annual and Summer (JJA) Discharge values for the Bow and Athabasca Rivers for the entire period of record for each station.

Station Name	***Drainage Area (km^2)***	***Glacier Cover %*****	***Annual Yield (Q per km^2)***	***Avg. Mean Annual Flow (m^3/s)***	***Avg. Mean June Flow (m^3/s)* / % of Annual Q***	***Avg. Mean July Flow (m^3/s)* / % of Annual Q***	***Avg. Mean August Flow (m^3/s)* / % of Annual Q***
Bow River at Banff	2210.0	3.3	6.50	39.3	124.7 / 26%	106.1 / 23%	66.2 / 14%
Athabasca River near Jasper	3872.7	7	8.23	87.3	236.3 / 22%	263.3 / 26%	204.3 / 20%

* Mean monthly values are based on years where 'full Julian year data' is available

** Bow Valley from Hopkinson & Young, 1998, Athabasca Watershed from Dr. Roger Wheate, personal communication

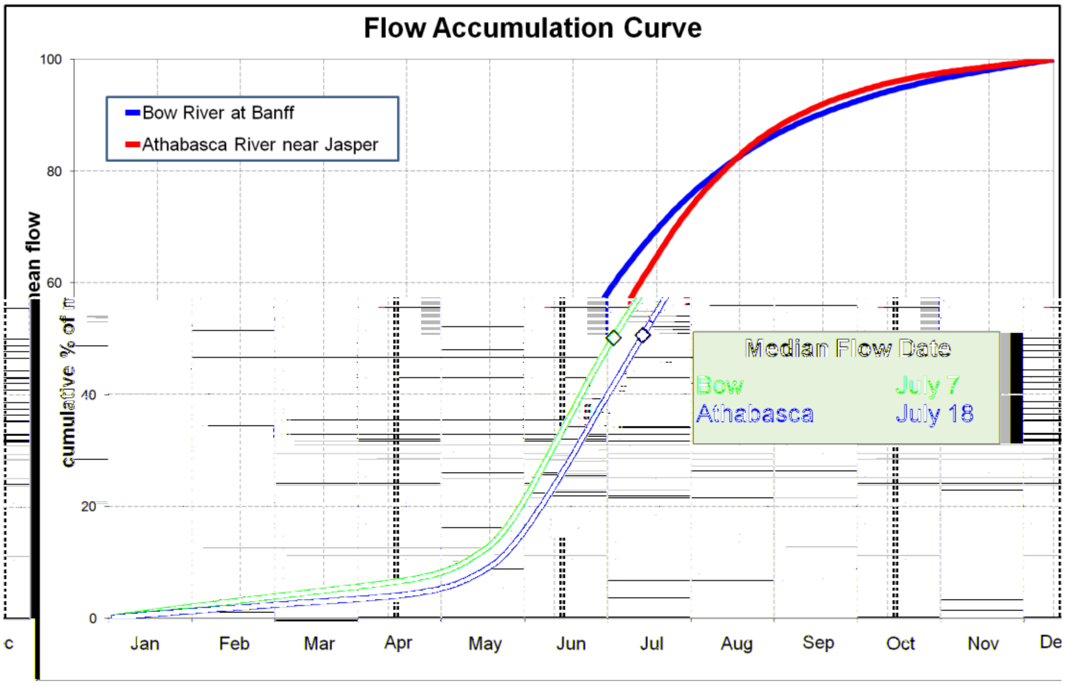


Figure 3.3: Flow accumulation curve of the Athabasca River near Jasper and the Bow River at Banff for the common 1971-2005 period.

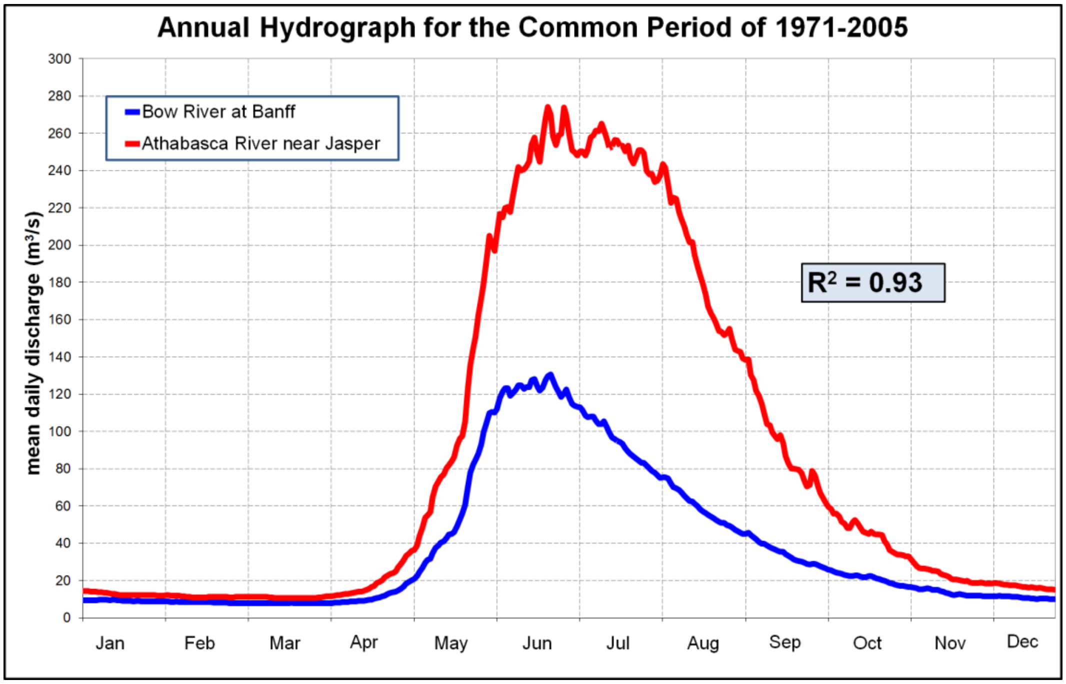
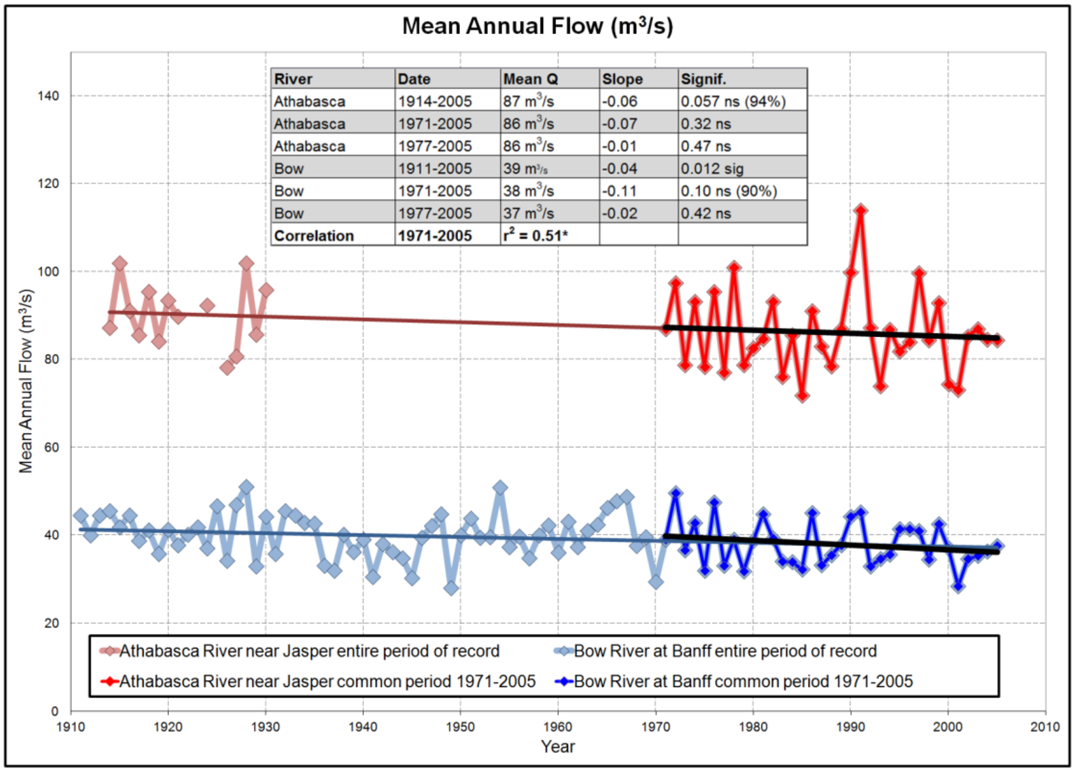


Figure 3.4: Mean Annual Hydrograph (1971-2005) for the Athabasca River near Jasper and the Bow River at Banff.

Individual analyses and comparative studies of the Bow and Athabasca records were carried out using four measures; mean annual flow, date of peak discharge, peak daily discharge, and CT date (Figures 3.5-3.7) over three time periods; the entire record (1910 or 1914-2005, the common period 1971-2005 and the period 1977-2005. Measures of the "spring pulse" are commonly used to indicate changes in streamflow timing trends (Stewart *et al*, 2005, Knowles *et al*, 2006). In this study the date of peak discharge was chosen to represent the peak of the spring melt event in both basins. However, the peak discharge of the Athabasca in 1978 is on September 5th, rather than within the normal range between mid-May and mid-July. Approximately 66 mm of precipitation fell in Jasper between Sept 2nd-6th, 1978 (mean September precipitation is only 35 mm) indicating that this discharge peak is probably related to a major fall rainstorm, the effects of which are also recorded in the Miette and Sunwapta records (see below). Therefore the

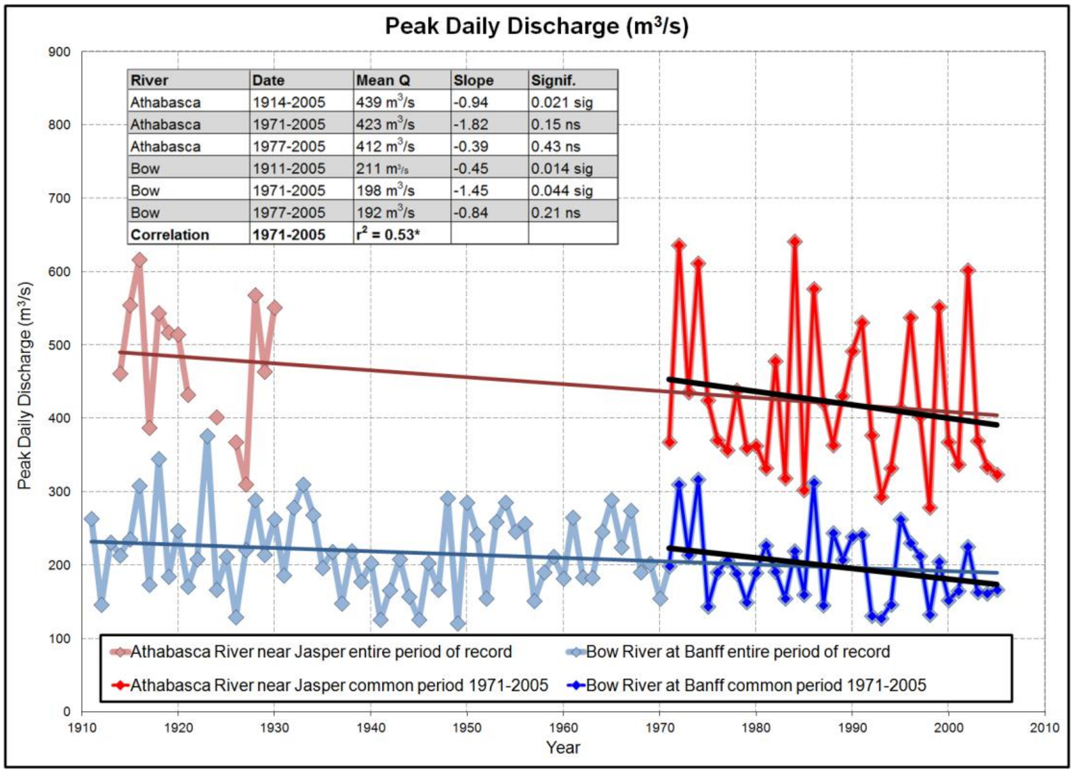


River	Date	Mean Q	Slope	Signif.
Athabasca	1914-2005	87 m^3/s	-0.06	0.057 ns (94%)
Athabasca	1971-2005	86 m^3/s	-0.07	0.32 ns
Athabasca	1977-2005	86 m^3/s	-0.01	0.47 ns
Bow	1911-2005	39 m^3/s	-0.04	0.012 sig
Bow	1971-2005	38 m^3/s	-0.11	0.10 ns (90%)
Bow	1977-2005	37 m^3/s	-0.02	0.42 ns
Correlation	**1971-2005**	**$r^2 = 0.51$***		

Figure 3.5: Comparison of mean annual discharges for the Athabasca and Bow rivers. Correlation is between annual discharge values, * denotes a significant correlation.

discharge data for June 6th (413 m^3/s) were substituted for September 5th (439 m^3/s) in the peak discharge analysis for the Jasper record.

Figure 3.5 shows the annual discharge records for the Athabasca and Bow and correlations between these streamflows over different time periods. The long Bow record has a significant decreasing trend through the 20th century. This confirms the general picture of 20th century decreases in discharge in the Cordillera reported in previous regional studies, some of which have used these data. Although there are no data for the Athabasca between 1930 and 1970, the entire record shows a similar negative trend which falls marginally below the 0.95 significance level. Both records are highly variable but strongly correlated ($r^2=0.51$). Trends over the shorter 1971-2005 interval are slightly

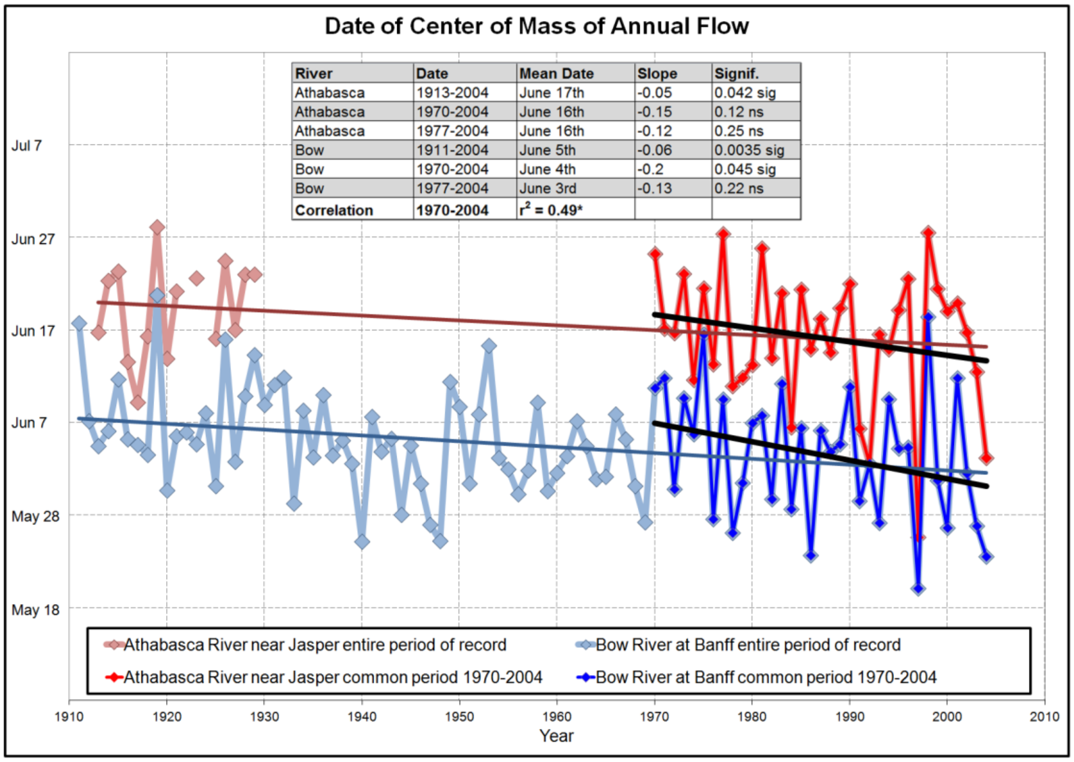


River	Date	Mean Q	Slope	Signif.
Athabasca	1914-2005	439 m^3/s	-0.94	0.021 sig
Athabasca	1971-2005	423 m^3/s	-1.82	0.15 ns
Athabasca	1977-2005	412 m^3/s	-0.39	0.43 ns
Bow	1911-2005	211 m^3/s	-0.45	0.014 sig
Bow	1971-2005	198 m^3/s	-1.45	0.044 sig
Bow	1977-2005	192 m^3/s	-0.84	0.21 ns
Correlation	**1971-2005**	**$r^2 = 0.53$***		

Figure 3.6: Peak daily discharge records for the Athabasca and Bow Rivers. Correlation is between peak daily discharge values, * denotes a significant correlation.

negative but none are statistically significant given the high variability and relatively low number of observations. Over the shortest 1977-2005[4] period the trend is effectively zero.

Both rivers show significant decreases in the magnitude of their peak daily discharges over the 20th century and though both show a greater rate of decrease over the shorter 1971-2005 interval only the Bow record is statistically significant (Figure 3.6). However, if the high streamflows immediately prior to the 1976 shift are excluded, neither river's trend is significant over the 1977-2005 period. The dates of peak discharge were analyzed but showed a poor relationship between the rivers (r^2 = 0.23, results not shown) and no significant trends. However, the dates of centre of mass of flow (CT, Figure 3.7) show a similar pattern to the trends in discharge magnitude (Figure 3.5). Both rivers



River	Date	Mean Date	Slope	Signif.
Athabasca	1913-2004	June 17th	-0.05	0.042 sig
Athabasca	1970-2004	June 16th	-0.15	0.12 ns
Athabasca	1977-2004	June 16th	-0.12	0.25 ns
Bow	1911-2004	June 5th	-0.06	0.0035 sig
Bow	1970-2004	June 4th	-0.2	0.045 sig
Bow	1977-2004	June 3rd	-0.13	0.22 ns
Correlation	**1970-2004**	**r^2 = 0.49***		

Figure 3.7: Date of centre of mass (CT) of annual flow of the Athabasca and Bow Rivers. Correlation is between CT dates, * denotes a significant correlation.

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[4] The first 5 years of the common continuous record precede the 1976 PDO 'shift". The shorter 1977-2005 period is entirely within the "warm" phase of the PDO.

show a shift to an earlier CT of ca. five (Athabasca) and seven days (Bow) over the entire record (ca. 90 years) but similar values (greater change) over the 1970-2004 period, although the trend in the Athabasca record is not significant. However, once again neither trend is significant for the shorter 1977-2004, post 1976 shift, period and the slope of the best fit line is reduced. The trend in the long continuous Bow record of CT dates is highly significant at the 99% confidence level demonstrating a striking movement towards earlier streamflow timing in the Bow watershed. The lower discharge volumes in the system decrease discharges and movement to an earlier CT date confirms that less water is moving through the system. As the Bow record is the longest high elevation record available for the southern Canadian Cordillera evaluation of these changes over time indicate that there are transformations occurring in the streamflow regimes in the mountains which will affect water availability though the entire watershed.

Figures 3.5-3.7 indicate similar trends and changes in streamflow volume, peak daily discharge and CT between the Athabasca and Bow records over their entire records and for the shorter contiguous intervals post 1971. However, the higher streamflow variability and shorter records for the Athabasca result in trends which are not statistically significant, particularly in the post 1976 interval when the higher streamflows of the "cold" 1947-1976 phase of the PDO are excluded. Generally there has been an overall decrease in streamflow volumes and an earlier date for the centre of mass on both rivers. Overall the general similarities between the Athabasca and Bow River data sets hold and, although the magnitude of their streamflow levels and timing of CT differ, the trends are similar. It seems reasonable to assume that changes in the Athabasca over the 20th century would have been similar to those that have occurred in the longer Bow record.

3.4 Comparison of the Athabasca and Miette Rivers

The Miette River joins the Athabasca immediately upstream of Jasper (Figure 3.8) and is gauged at the bridge of Highway 16 about 1.5km above the junction. The Athabasca is gauged at the Maligne Road Bridge about 5km downstream of the junction. As there is no significant surface contribution to the Athabasca between these points, the contribution of the basin above Jasper can be estimated by subtracting the daily Miette discharge from the Athabasca figure to isolate the record for the Athabasca River upstream of Jasper.

The Athabasca above Jasper carries meltwater from the Columbia, Chaba, and Hooker Icefields and the basin has ca. 8% glacier cover. The Miette basin has a glacial cover of ca. 0.2% and ranges in elevation from 1050m (Jasper) to 3100m above sea level. Both the Miette and Athabasca gauge records have ‘full Julian year data’ for 1915-1920 and 1976-2005. Although the earlier six year period is too short for trend analysis the data between the two rivers over this short interval are comparable but are not used in this study as the focus here is on changes in long term trends. Therefore the major comparison uses data from the 1976-2005 common period entirely within the “warm phase” of the PDO. Although the Athabasca basin is about five times larger and has a greater water yield per unit area (Table 3.3) than the Miette, comparison of these records allows a first order estimate of differences in regime resulting from differences in the glacier contribution (Figure 3.9). Previous studies e.g. by Rood *et al*, 2005, found that although many high elevation rivers in western North America showed decreasing trends in annual discharge, some rivers with large glacial melt contributions did not show any significant change.

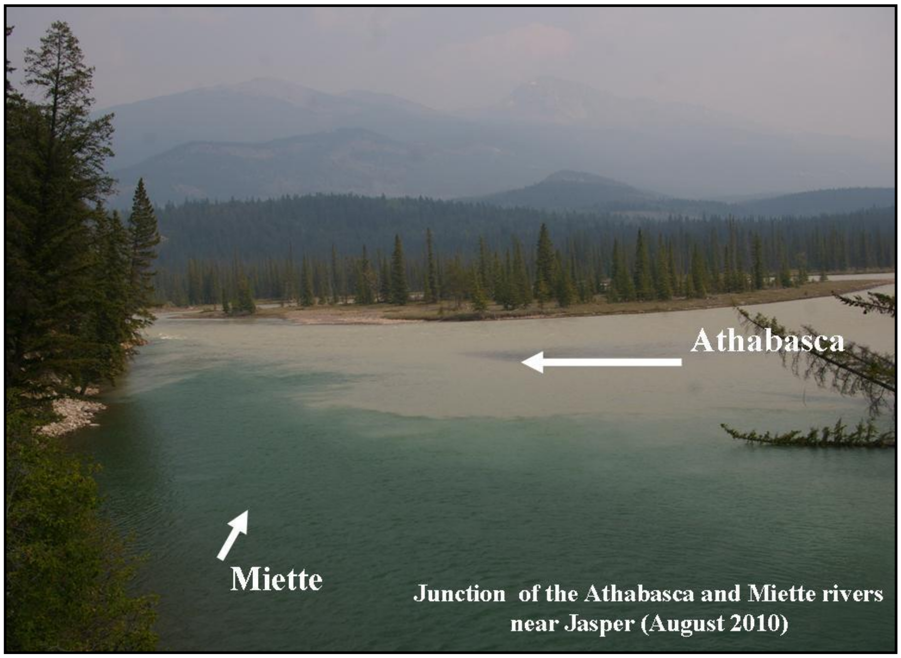


Figure 3.8: The junction of the Athabasca and Miette Rivers. Photo courtesy of Dr Brian Luckman.

Table 3.3: Annual and summer (JJA) discharge for the Athabasca and Miette Rivers for the 1976-2005 period of record.

Station Name	*Drainage Area (km^2)*	*Glacier Cover %***	*Annual Yield (Q per km^2)*	*Avg. Mean Annual Flow (m^3/s)*	*Avg. Mean June Flow (m^3/s)* / % of Annual Q*	*Avg. Mean July Flow (m^3/s)* / % of Annual Q*	*Avg. Mean August Flow (m^3/s)* / % of Annual Q*
Athabasca River near Jasper	3872.7	7	8.23	87.3	236.3 / 22%	263.3 / 26%	204.3 / 20%
Miette River near Jasper	628.5	0.2	6.14	10.4	40.5 / 32%	27.2 / 22%	13.4 / 11%
Athabasca River above Japer	3244.2	8	8.60	75.6	192.9 / 21%	226.9 / 25%	184.7 / 21%

* Mean monthly values are based on years where 'full year data' is available
** Glacier Cover values from Dr. Roger Wheate, personal communication

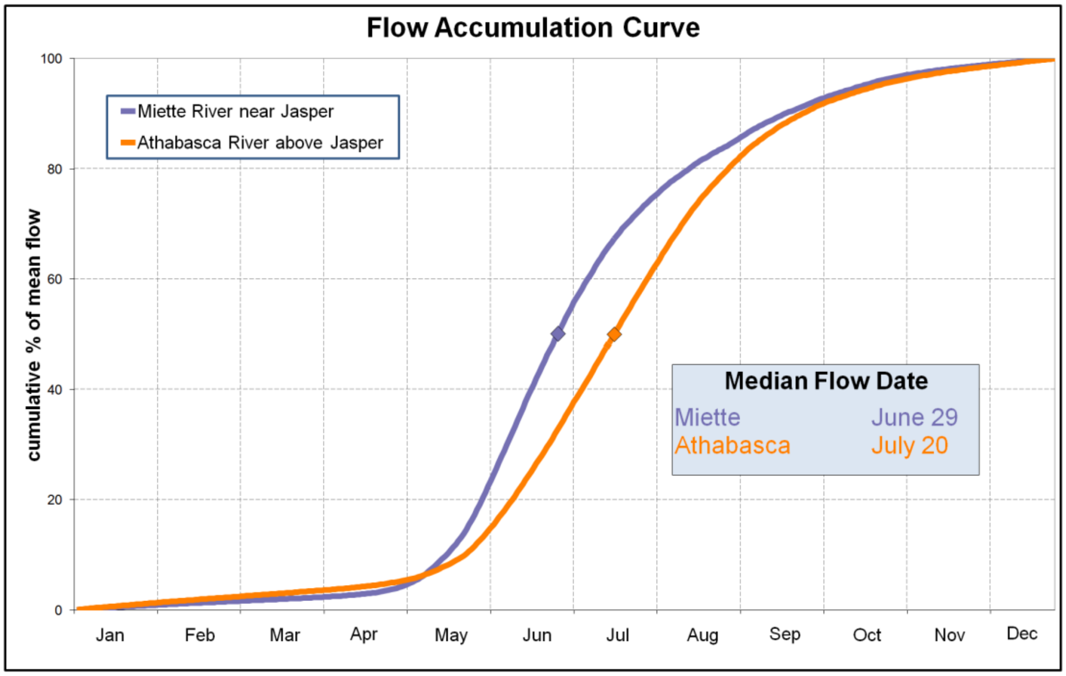


Figure 3.9: Flow accumulation curve of the Athabasca River above Jasper and the Miette River near Jasper for the common 1976-2005 period.

The two data sets are compared using the same hydrological measures as the Athabasca-Bow comparison. However, when the spring peak discharge data for the Athabasca above Jasper are recalculated by subtracting the Miette discharge, the highest discharge

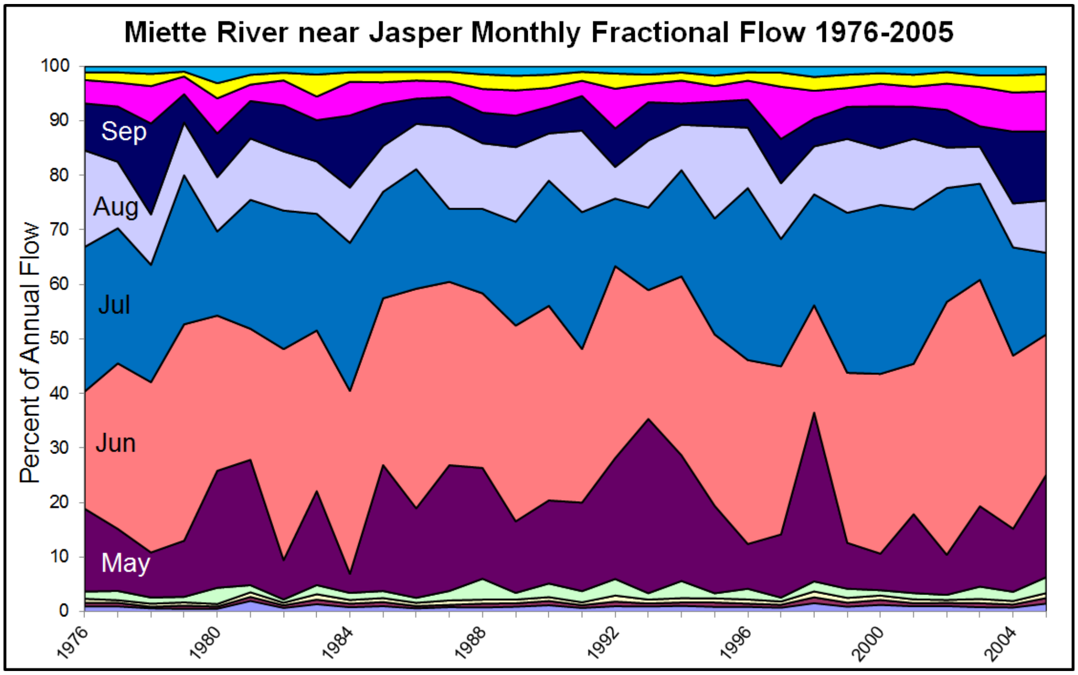


Figure 3.10: Monthly Fractional Flow of the Miette River near Jasper for 1976-2005.

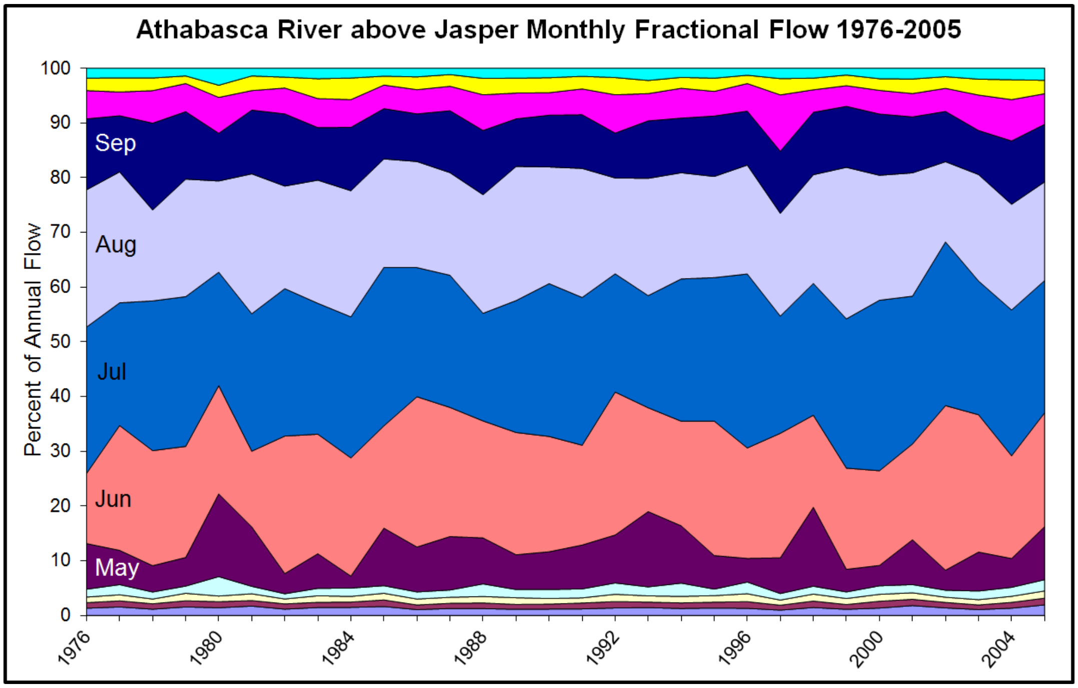


Figure 3.11: Monthly Fractional Flow of the Athabasca River above Jasper for 1976-2005.

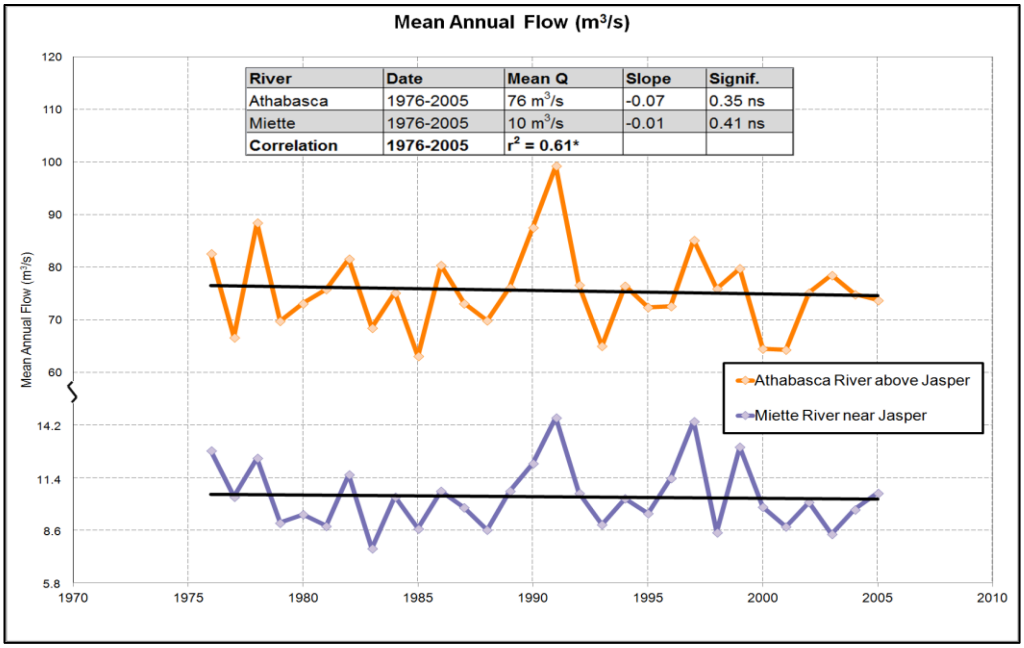
in 1978 was on July 11th, not June 6th. Therefore the July 11th value is substituted for the Sept 5th value as the spring peak for the Athabasca above Jasper. The high discharge (57.5m^3/s) for the Miette on September 4th reflects the September 2nd-6th rainfall event at Jasper but was only the third highest discharge in that year. The highest discharge (81.8m^3/s) was on June 6th which was the spring melt peak in that year.

The flow accumulation curve (Figure 3.9) and fractional flow data (Figures 3.10, 3.11, Table 3.3) indicate differences in the regime of these two rivers. Although the Athabasca has a relatively even distribution of streamflow in June, July and August with maxima in July, almost a third of the Miette discharge occurs in June and is generally three times greater than the August discharge. On average greater streamflow volumes occur in May (15%) on the Miette than in August. The median flow date occurs 21 days earlier on the Miette (June 29th) than the Athabasca (July 20th, Figure 3.11). Table 3.4 summarizes the findings of the four measures over the entire common period of record (1915-1920, 1976-2005). Although the sample size is small, mean flows and peak daily discharges for both rivers are greater in the 1915-1920 period and the peak discharge and CT dates for the Miette are earlier. Although the sample depth is too small for significance testing, similar patterns are noted for the same periods in the longer Bow Records (see PDO analysis, below).

Table 3.4: Miette River near Jasper and Athabasca River above Jasper mean values for the common periods, no trends in these series were found to be significant.

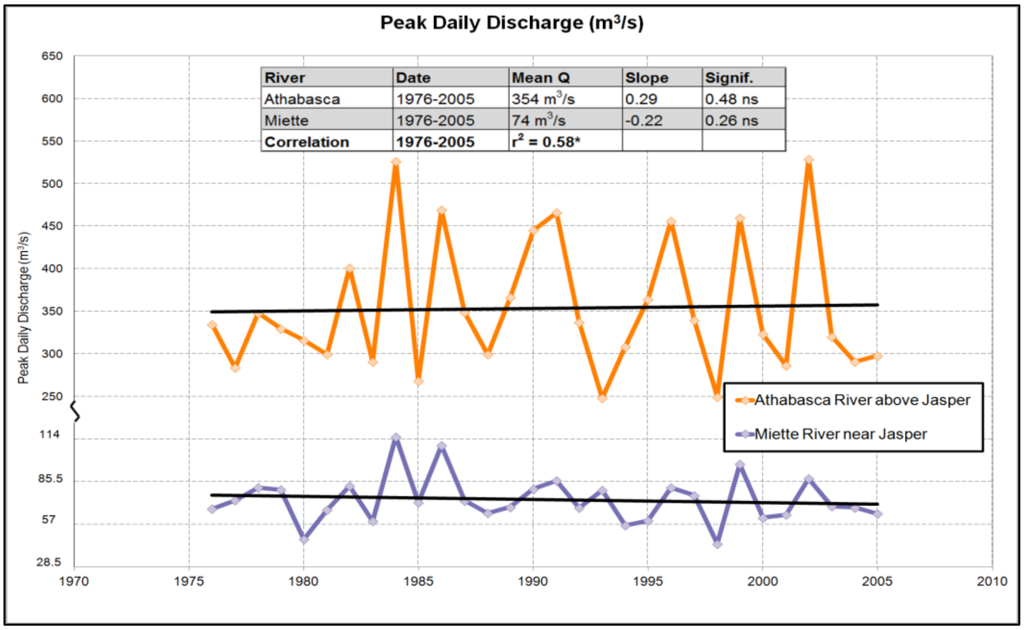
Station Name	*Mean Annual Flow (m^3/s)*	*Peak Daily Discharge (m^3/s)*	*Peak Date*	*CT date*
Miette River near Jasper – 1915-1920	11.4	82.4	June 21	July 15
Miette River near Jasper – 1976-2005	10.4	73.6	June 9	July 12
Athabasca River above Japer – 1915-1920	80.6	458.8	July 4	July 26
Athabasca River above Japer – 1976-2005	75.6	354.8	July 4	July 24

The mean annual flow and magnitude of peak daily discharge data for both rivers show large interannual variability and no significant trend over the period of record (Figures 3.12, 3.13). Both basins show a trend towards peak daily discharges later in the year



River	Date	Mean Q	Slope	Signif.
Athabasca	1976-2005	76 m^3/s	-0.07	0.35 ns
Miette	1976-2005	10 m^3/s	-0.01	0.41 ns
Correlation	**1976-2005**	**r^2 = 0.61***		

Figure 3.12: Mean annual flow of the Athabasca River above Jasper and the Miette River near Jasper 1976-2005. Correlation is between annual flow values, * denotes a significant correlation.



River	Date	Mean Q	Slope	Signif.
Athabasca	1976-2005	354 m^3/s	0.29	0.48 ns
Miette	1976-2005	74 m^3/s	-0.22	0.26 ns
Correlation	**1976-2005**	**r^2 = 0.58***		

Figure 3.13: Peak daily discharge of the Athabasca River above Jasper and the Miette River near Jasper for 1976-2005. Correlation is between peak daily discharge, * denotes a significant correlation.

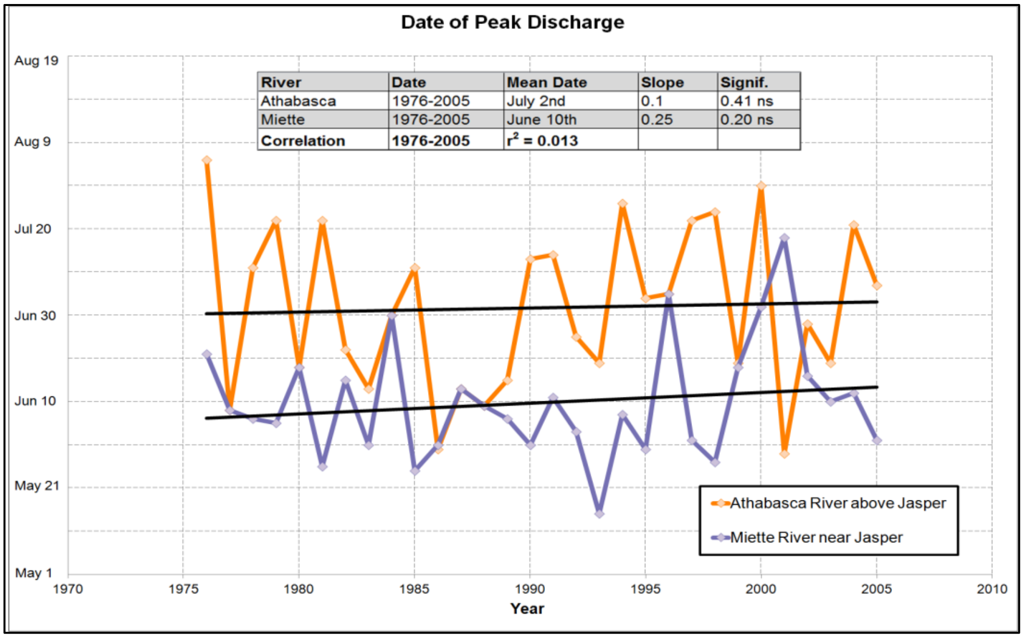


Figure 3.14: Date of peak discharge of the Athabasca River above Jasper and the Miette River near Jasper for 1976-2005. Correlation is between dates of peak discharge.

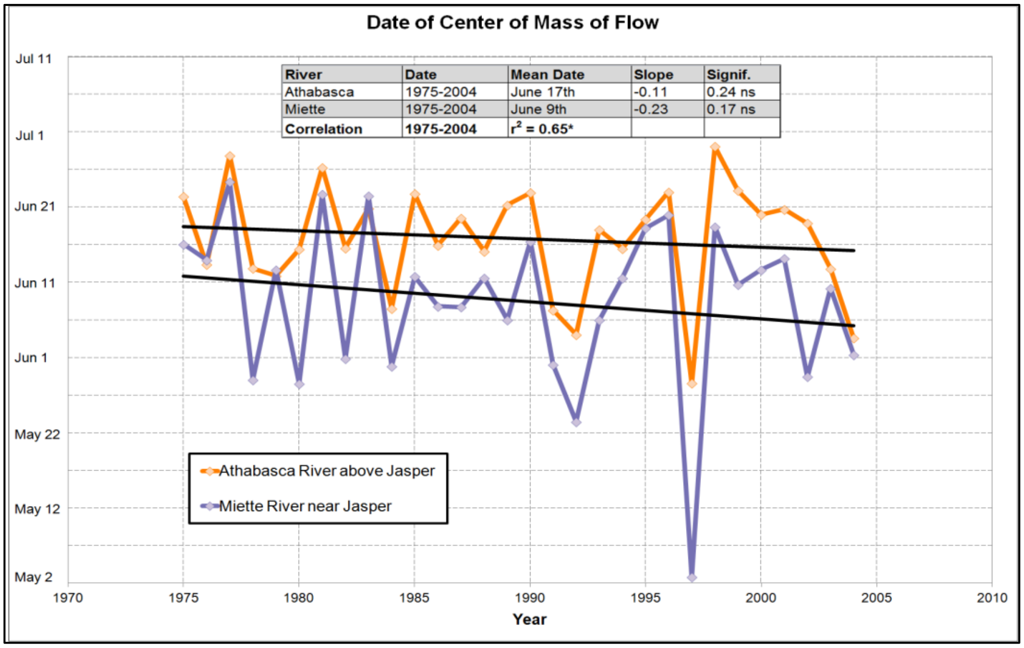


Figure 3.15: CT date of the Athabasca River above Jasper and the Miette River near Jasper for 1975-2004. Correlation is between CT dates, * denotes a significant correlation.

(Figure 3.14), though neither trend is statistically significant. Conversely, the strongest trends are for an earlier CT in both basins (Figure 3.15), particularly for the Miette but neither trend is statistically significant. The CT dates of June 9th (Miette) and June 17th (Athabasca) are much closer together than the calendar year median flow dates over the common 1975-2005 interval (Figure 3.9). This indicates that the Miette River has a greater proportion of streamflow occurring in the late fall to early winter period as the CT date begins to analyze streamflow from October 1st where as the median flow date is for the calendar year period. The CT date and streamflow volumes are strongly correlated between the two drainage basins with similar patterns through time indicating a strong common climatic control. These data indicate that the overall discharge trends are the same for the two rivers but the Miette River has lower discharge and reaches its median date before the Athabasca 70% of the time. However, in some years the date of peak discharge occurs on the same day in both rivers and in 2001 the Miette peak discharge is later than the Athabasca (Figure 3.14) suggesting a differential contribution such as a large-scale rainfall event. There are also years where the Miette River peaks much earlier than the Athabasca River (i.e. 1981, 1985, 1994, and 1998). These anomalies suggest more localized precipitation or snowmelt events that contribute differentially to the two catchments. The overall similarities between these two rivers suggest they have similar long term trends but there are differences due to localized input events and some differences related to the amount of glacial inputs for each river.

3.5 The Sunwapta River Record

The Sunwapta River is a major tributary of the Athabasca River and its headwaters drain directly from the Athabasca Glacier. The gauge site was covered by the glacier until the late 1930’s and is situated immediately downstream of the proglacial Sunwapta Lake. The lake first appeared in the early 1940s (Luckman, 1986) and the calving ice front was approximately 0.2km upstream of the gauge when it was installed in 1948. Subsequently the glacier has receded ca. 0.9km. The lake reached its maximum size ca. 1967 (0.6km long) and has subsequently been partially filled by sediment and the delta front is now close to the ice front position of the early 1950’s, ca. 0.3km upstream of the gauge (Luckman pers. comm., 2011). The Sunwapta gauge provides the longest ice-proximal proglacial drainage record in Canada. Sunwapta Lake receives drainage from the Athabasca Glacier and several smaller glaciers on the east side of the forefield and the drainage basin is presently about 61% ice covered (Figure 3.16). The WSC installed the gauge in 1948 (Figure 3.17) and maintained a more or less continuous seasonal record from 1948-1995 (the lake and river are normally frozen for at least six months a year). Apart from a short early report (Matthews, 1956) this record has not previously been studied.

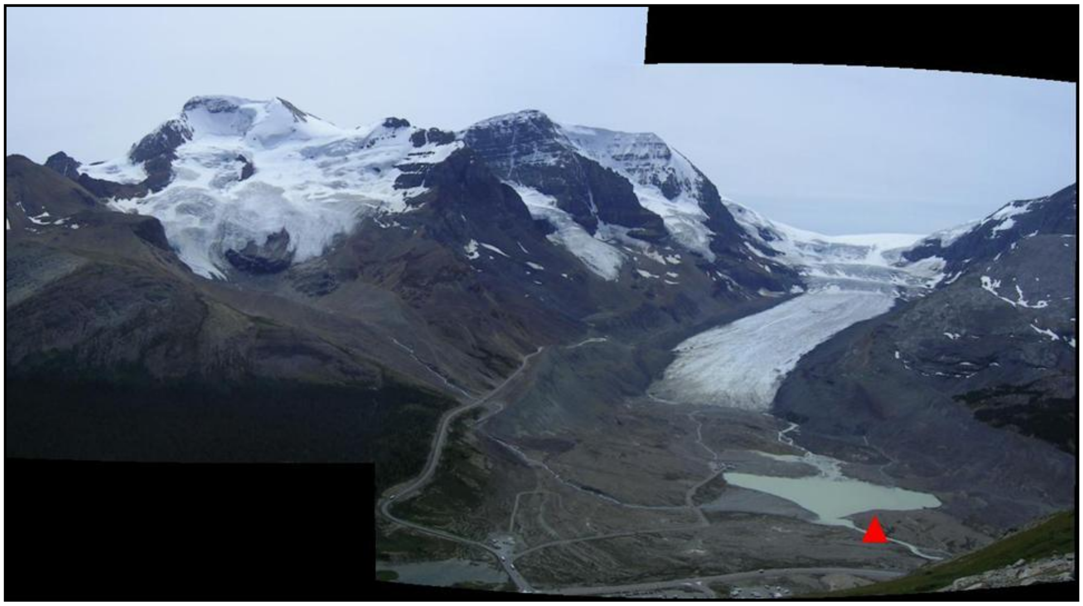


Figure 3.16: The Athabasca Glacier at the head of the Sunwapta River 2006. The drainage flows through Sunwapta Lake and down the Sunwapta River past the Water Survey of Canada gauge (denoted by red triangle). Photo courtesy of Dr Brian Luckman.

The seasonal and fragmented nature of the Sunwapta record necessitates a slightly different approach to database development. The absolute earliest and latest days where streamflow was recorded at this gauge are April 21st and November 17th. Of the 49 years with data, 42 years have complete daily coverage from June 1st until September 30th but only 28 have data from May 1st until October 31st. In those years with May through October data, May and October totals are 3.20%, (range 0.73% to 11.94%) and 3.22% (range 0.83% to 6.14%), respectively. The date of peak discharge and therefore the peak discharge volumes for the June to September records for these 28 years are identical to those from the May-October records. The 28 years with May-October have earlier CT values (mean date July 17th, range July 3rd-29th) than the June to September record (mean date July 29th, range July 23rd-August 6th) as would be expected for the longer record. As the average difference in the earliest CT date in these two records is only seven days, the possibility to add 14 years of summer streamflow data is a more important consideration in selecting the 42 year-long record of June- September data for the Sunwapta analysis.

Figure 3.17: The Sunwapta River at Athabasca Glacier gauging station August 1, 2008.

The average date of peak discharge for the Sunwapta is about one month later than the Athabasca over the1971-1996 record. However, four of the Sunwapta peak discharge dates are in September (including 1978, discussed earlier) and could be the result of fall storm events. During the summer ablation season the snow line migrates up the

Athabasca Glacier and, in recent years, reaches the lower icefall, exposing ca. 2 – 2.25 km^2 of relatively clean glacier ice (ca. 10-15% of the basin) by the end of the melt season. Therefore a rapid runoff response would be expected from the glacier and the largely unvegetated forefield during fall/ late summer rainstorms that would significantly increase proglacial discharge. Precipitation records from Jasper indicate significant precipitation events preceding the high streamflow events at Sunwapta in 1957, 1978 and 1982. However, 1967 had a late spring melt and large volumes of glacier melt late in the season.[5] Therefore the peak discharge on September 1st in 1967 is considered the melt peak and was not adjusted in this study. The peak discharge dates of the other three years were adjusted to reflect the summer melt period namely; September 6th, 1957 to August 18th; September 3rd, 1978 to July 26th and September 8th, 1982 to July 31st.

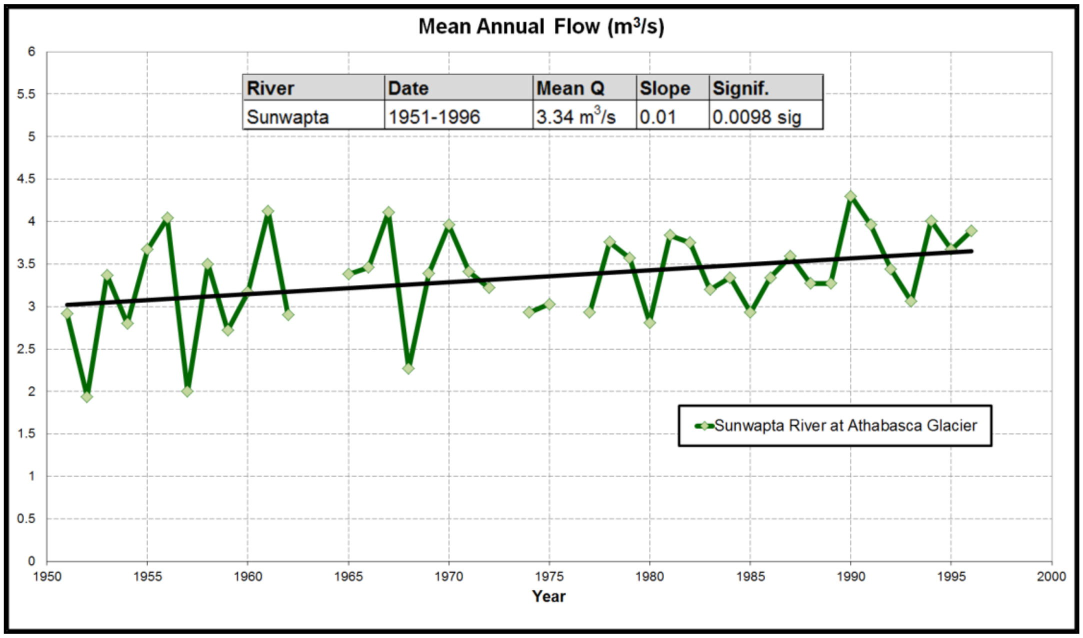


Figure 3.18: Mean June 1 – September 30 discharge of the Sunwapta River at Athabasca Glacier.

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[5] The Castleguard cave was flooded late in the season (D.C.Ford pers. comm. to Luckman , 1967) and Peyto Glacier has a strongly negative summer balance in this year (Demuth & Pietroniro, 2003)

The four hydrological measures were examined for the Sunwapta River June 1 – September 30 data. The mean annual (June- September) flow for the Sunwapta River (Figure 3.18) shows a significant increase (99% level) over the 1951-1996 record. This suggests a probable increased contribution to streamflow from glacier melt over time as regional snow course records (Watson *et al*, 2008) and the Banff precipitation record (see Chapter 4) indicate decreased snowpacks following the 1976 PDO shift. There is no significant trend to the values for peak daily discharge (Figure 3.19) with a mean of 8.77m^3/s with or 8.63m^3/s without adjustments for September rainfall events as the slope and significance values are barely affected by the change. The date of peak discharge (Figure 3.20) is highly variable and does not show a significant trend for either adjusted or absolute values. However, the CT data (Figure 3.21) do show a significant trend

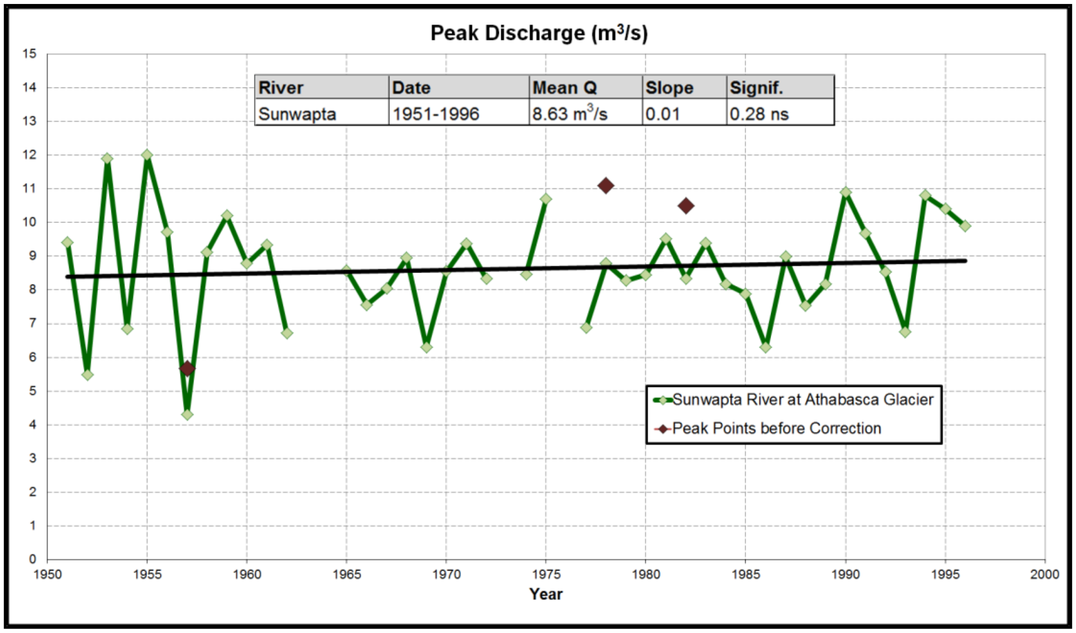

Figure 3.19: Peak daily discharge for the Sunwapta River 1951-1996. The maroon diamonds are values for September storms replaced by early melt events in these analyses (for explanation see text).

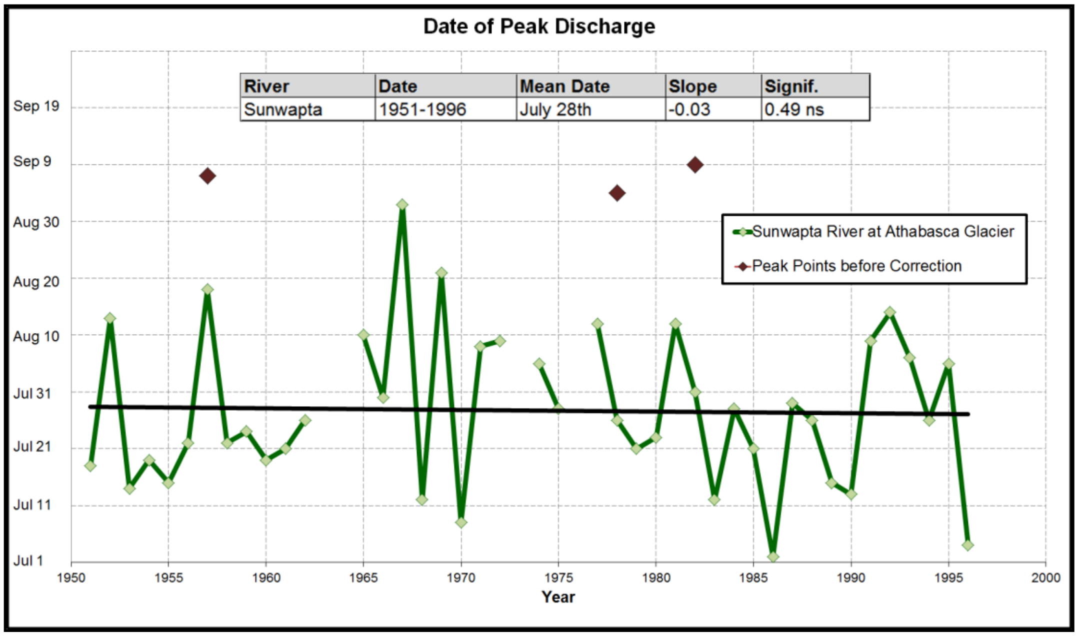

Figure 3.20: Date of peak spring-summer discharge (June 1 – September 30) of the Sunwapta River at Athabasca Glacier. The original dates of fall rainfall events that were corrected are also shown.

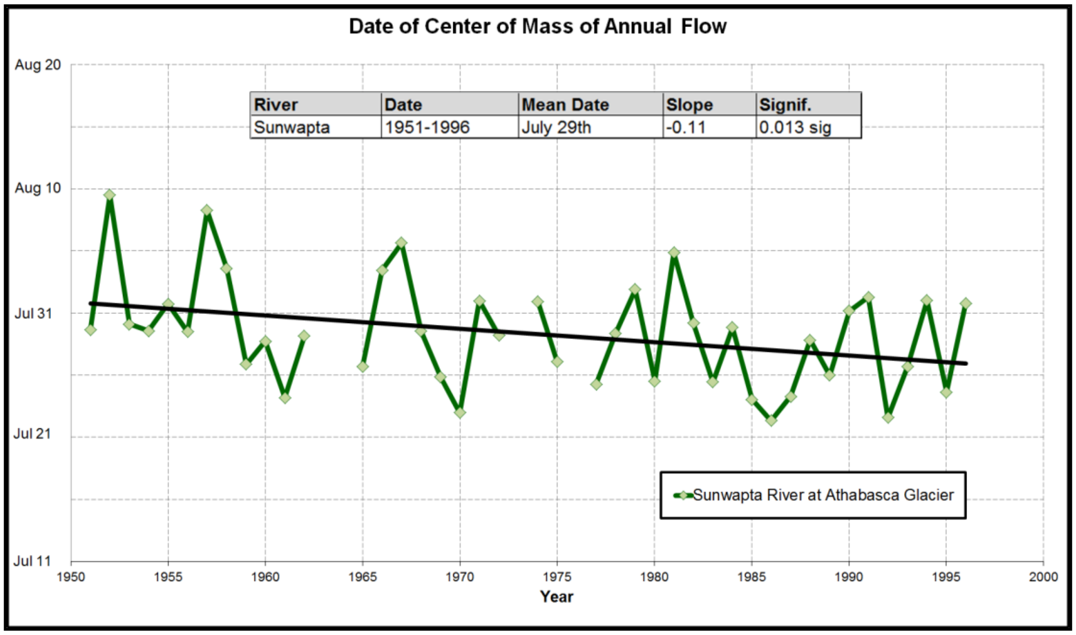

Figure 3.21: CT date in the June 1 – September 30 period for the Sunwapta River at Athabasca Glacier. These data were not adjusted for rainfall events (see text).

towards an earlier timing of the centre of flow[6]. These results indicate earlier melt at this site but little change in the peak daily discharges.

Table 3.5: Athabasca River near Jasper and Sunwapta River at Athabasca Glacier mean values for the seasonal June 1 – September 30 period for 1971-1996.

Station Name	*Mean Annual Flow (m^3/s)*	*Peak Daily Discharge (m^3/s)*	*Peak Date*	*CT date*
Athabasca River near Jasper 1971-1996	200.6	429.2	June 26	July 23
Sunwapta River at Athabasca Glacier 1971-1996	3.4*	8.8	July 28	July 28

* Trends over this period are significant

In order to investigate whether these changes in the Sunwapta are visible in the downstream Athabasca record, a truncated June1- September 30 record was developed for the Athabasca record near Jasper and compared with the Sunwapta record for the 1971-1996 common period (Table 3.5). The mean annual flow and peak daily discharge data do not show any relationship (r^2 = 0.30 and 0.00 respectively). Although the mean flow for the Sunwapta shows a significant negative trend, the discharges of the two stations are of such different magnitudes that there is little detectable effect. However, the dates of peak discharge show opposing though non-significant, trends (Figure 3.22). Although the Athabasca generally peaks earlier in the year there are four years during the common period when both peak on the same date. These all occur in early July and may reflect periods of rapid glacier melt at the glacier. The higher elevation of the Sunwapta basin generally results in peak discharge 32 days later than the Athabasca. The general pattern of Athabasca results from differences in the elevation of the two basins and the timing of snowmelt across the basins. The opposing trends seen in Figure 3.22 are not significant and reflect the different characters of the basin. The Sunwapta river is only tied to glacial melt at a higher elevation and the Athabasca River is sometimes dominated by these same glacial effects but at other times the larger snowmelt contributions in the

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[6] Inclusion of the high September flows has minimal effect as it moves the CT dates one day later in 1967 and 1978 with no change in 1982.

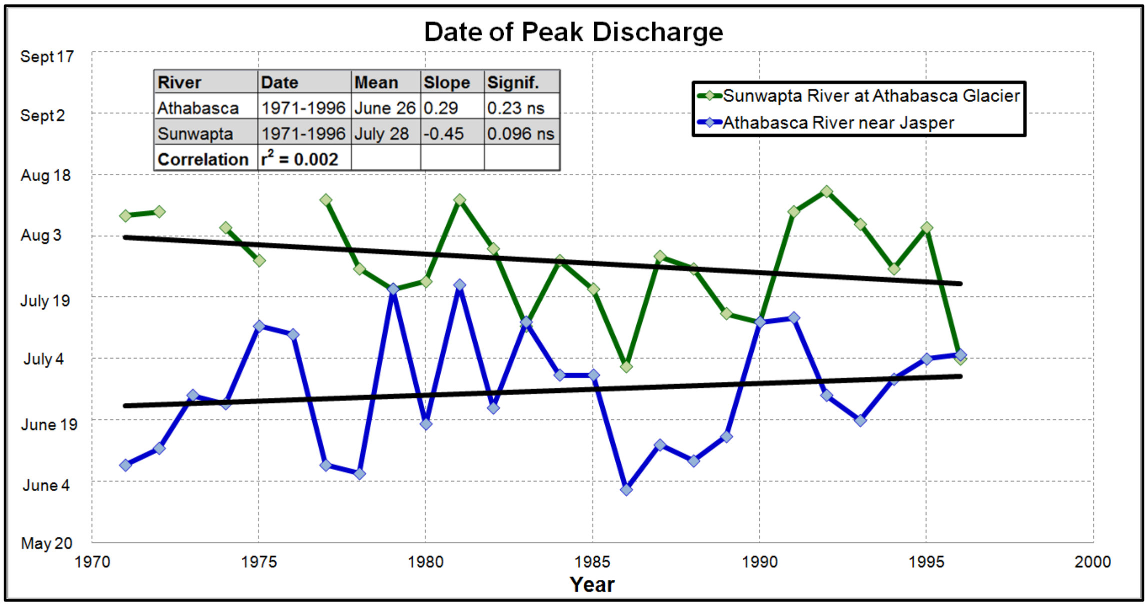
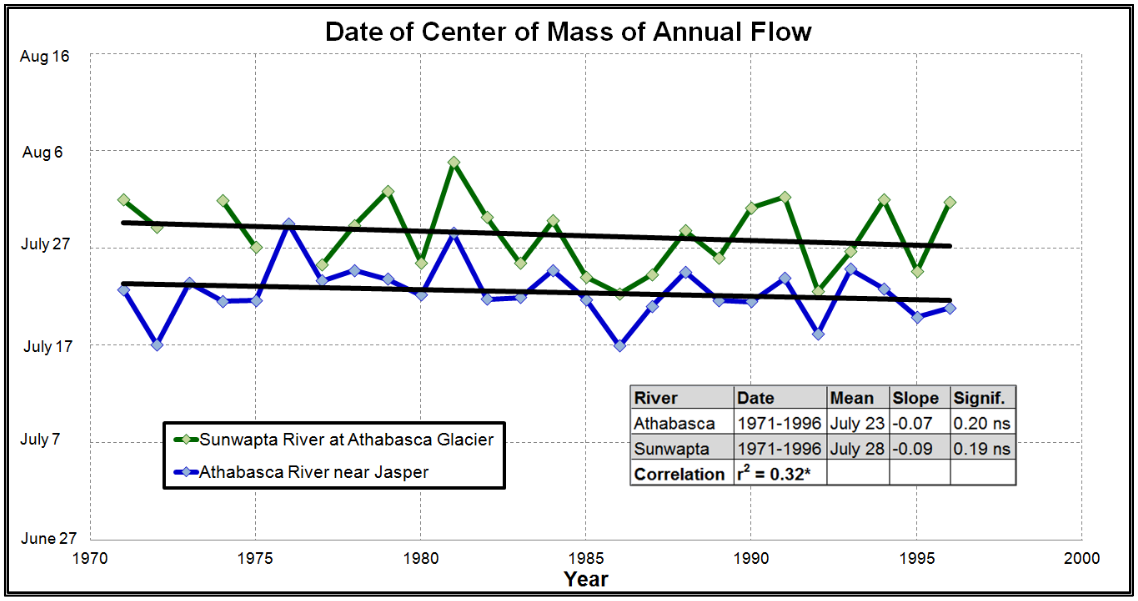


Figure 3.22: Date of peak discharge of the Athabasca River near Jasper and the Sunwapta River at Athabasca Glacier for 1971-1996. The September peak adjustments have been made on these datasets. Correlation is between dates of peak discharge.

basin cause earlier peak discharge timing due to the ability of snow to melt quicker at the lower elevations of the Athabasca basin. The overall trend on the Athabasca (as seen in Figure 3.6) is to earlier timing of peak discharge but this seasonal analysis shows a trend to later peak discharge dates. This is possibly a reflection of the importance of changes in snow cover over the entire Athabasca basin that is allowing for increased spring (March through May) streamflow to cause earlier peak. In the Sunwapta basin these effects are not seen as it is at a higher elevation and so there is little discharge occurring during the early spring period. Therefore the total melt volume for each river is causing a trend to earlier peak discharge but when the major snowmelt contribution is not accounted for the Athabasca basin this trend does not hold. Although the dates of peak discharge are variable, the CT dates (Figure 3.23) for both rivers show similar, though non-significant, trends towards an earlier CT date and covarying year to year fluctuations. The Athabasca CT date averages ca. five days earlier (Range = 1-12 days) than the Sunwapta reflecting earlier snowmelt in the larger basin. This again shows the importance of the snowmelt in the larger basin and its contributions to overall discharge timing, also the range in elevations of the contributing areas effects when the CT date can occur. Collectively these comparative data indicate the smaller Sunwapta drainage is more responsive to local conditions compared to the Athabasca where response is integrated over many subbasins.



River	Date	Mean	Slope	Signif.
Athabasca	1971-1996	July 23	-0.07	0.20 ns
Sunwapta	1971-1996	July 28	-0.09	0.19 ns
Correlation	**r^2 = 0.32***			

Figure 3.23: CT date of the Athabasca River near Jasper and the Sunwapta River at Athabasca Glacier for 1971-1996. No adjustments for September flows made in this analysis. Correlation is between CT dates, * denotes a significant correlation.

3.6 The Effects of Differences in Glacier Cover

The overall effects of differences in glacier cover between these four basins can be seen in Figures 3.24 and 3.25. The May through October seasonal flow accumulation curves (Figure 3.24) show differences in almost a month in the median flow date with sequence ranked from the lowest (Miette, 0.2%) to highest (Sunwapta, 61%) glacier cover. The relative daily discharge pattern (Figure 3.25) also shows the clear shift in snowmelt contributions over the summer season with increasing glacier cover augmenting the later season streamflow. Although these records are not directly comparable they clearly show the likely progression of changes in streamflow regime that would result from the loss of glacier cover within these, or similar, basins.

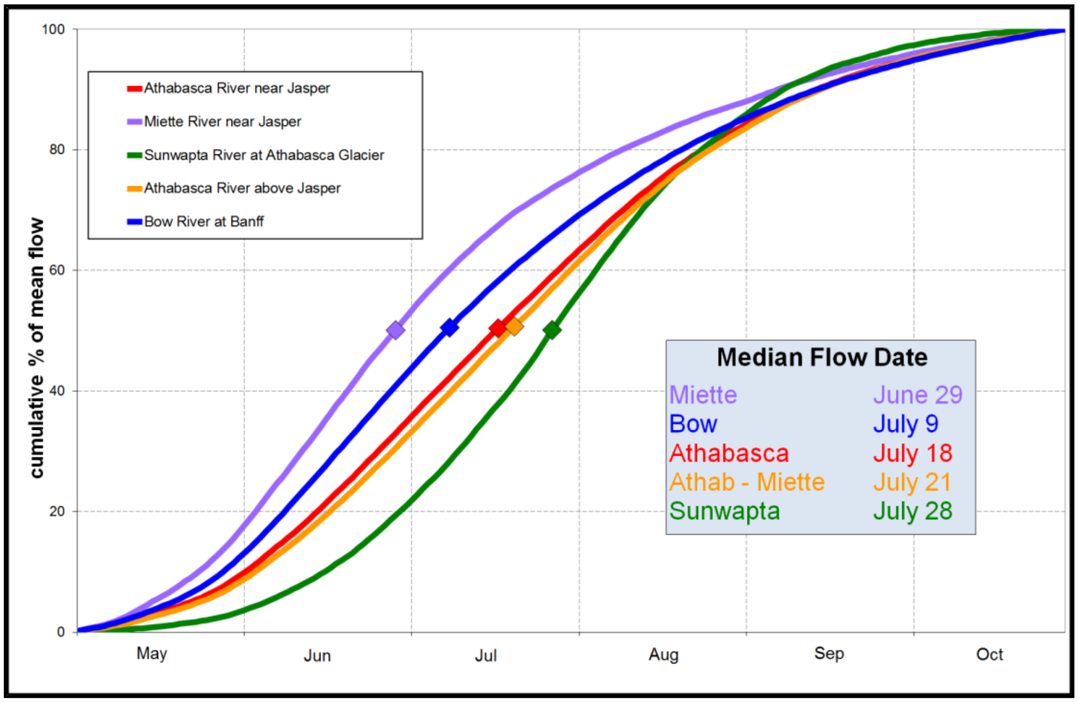


Figure 3.24: Seasonal (May through October) flow accumulation curves for the five streamflow records analyzed in this study for the 1976-1996 common period.

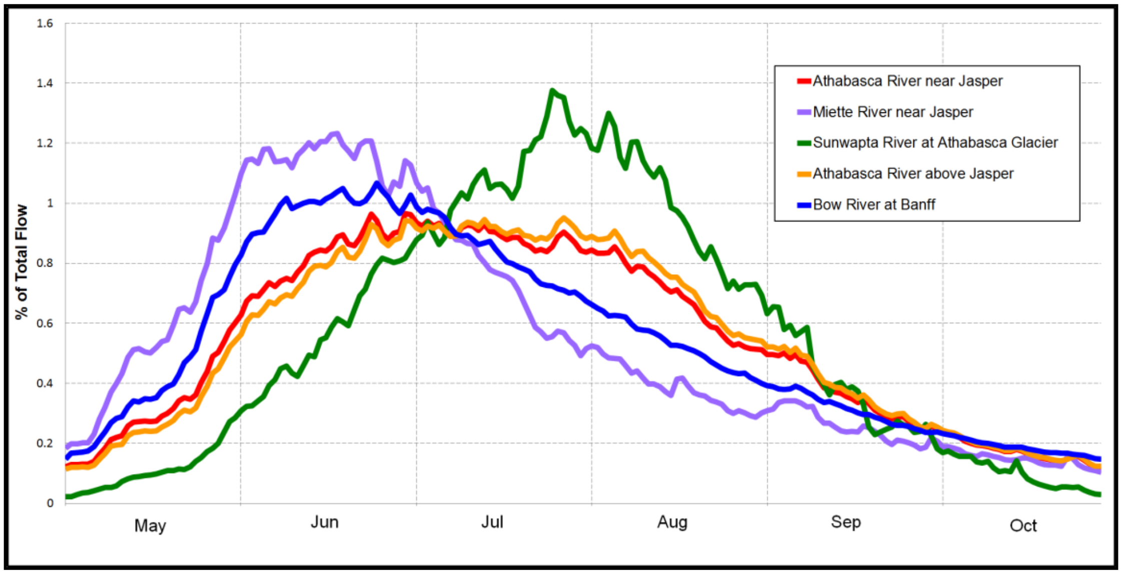


Figure 3.25: Daily percentage of seasonal (May through October) flow for the five streamflow records analyzed in this study for the 1976-1996 common period.

3.7 The Pacific Decadal Oscillation

Studies of streamflow in Western North America have shown a link between the Pacific Decadal Oscillation (PDO) and streamflow variations (Mote *et al*, 2005, Rood *et al*, 2005, Moore & McKendry, 1996, Demuth & Pietroniro, 2003, St Jacques *et al*, 2010). Mantua and Hare (2002) identified 20th century shifts in the PDO in 1925, 1947, and 1977. The records for the Bow and, to a lesser extent, the Sunwapta span different phases of the PDO and the following analysis concentrates on these two records. Although there are insufficient data for a detailed analysis, there is also limited evidence for PDO influence on the Athabasca and Miette Rivers.

3.7.1 The Bow Record

As was discussed in section 3.3 above, the Bow record shows a significant linear decrease in streamflow over the 20th century record. However this record spans four phases of the PDO, two "cool phases" (1911-1924 and 1947-1976) and two "warm phases" (1925-1946 and 1977-2005). Each includes 20-30 years of data except for the earliest 13 year period for which data may be less reliable due to the smaller sample size and the inclusion of some estimated data from manual measurements. As previous studies suggest that the PDO is a significant influence on streamflow records in western North America it is important to examine potential relationships between the PDO and the Bow discharge. These effects are summarized in Table 3.6 and illustrated in Figure 3.26. Figures 3.27-3.30 show linear analyses of the Bow record and its subdivision according to individual PDO phases.

Table 3.6: Bow River at Banff mean values for the PDO phases through the 20th century.

PDO phase	*Mean Annual Flow (m^3/s)*	*Peak Daily Discharge (m^3/s)*	*Peak Date*	*CT date*
"Cool 1" 1911-1924	41.1*	234	June 19	June 8
"Warm 1" 1925-1946	39.0*	206*	June 13	June 5*
"Cool 2" 1947-1976	40.7	221	June 17	June 4
"Warm 2" 1977-2005	37.3	192	June 12	June 3
	* Trends over this period are significant			

Figure 3.26 presents composite annual hydrographs for the four PDO “phases” that show clear differences in the streamflow regime between the PDO phases. Both “cool” phases show higher streamflow volumes in June and July and a longer recession from these peaks through July and August. In particular the earliest period shows later onset of spring flows, higher peaks and a longer recession than any other period. Mean discharges during both “cool” phases are 2-3 m^3/s higher (Figure 3.27) than in the two “warm” phases with June and early July periods often 20-25 m^3/s greater (Figure 3.26). Although the mean annual flow of the Bow shows a significant decrease over the entire record (Figure 3.5), the trends within the four sub-periods are different (Figure 3.27). Although mean flows for the two early phases are not significantly different both show strong and highly significant negative trends with a sharp increase in streamflow at the time of the 1927 and 1946 “shifts”. The 1947-76 and 1977-2005 periods show no trend but the means are statistically significantly different. Peak daily discharge values over the entire record show a decreasing trend over the entire period of record (Figure 3.6) though

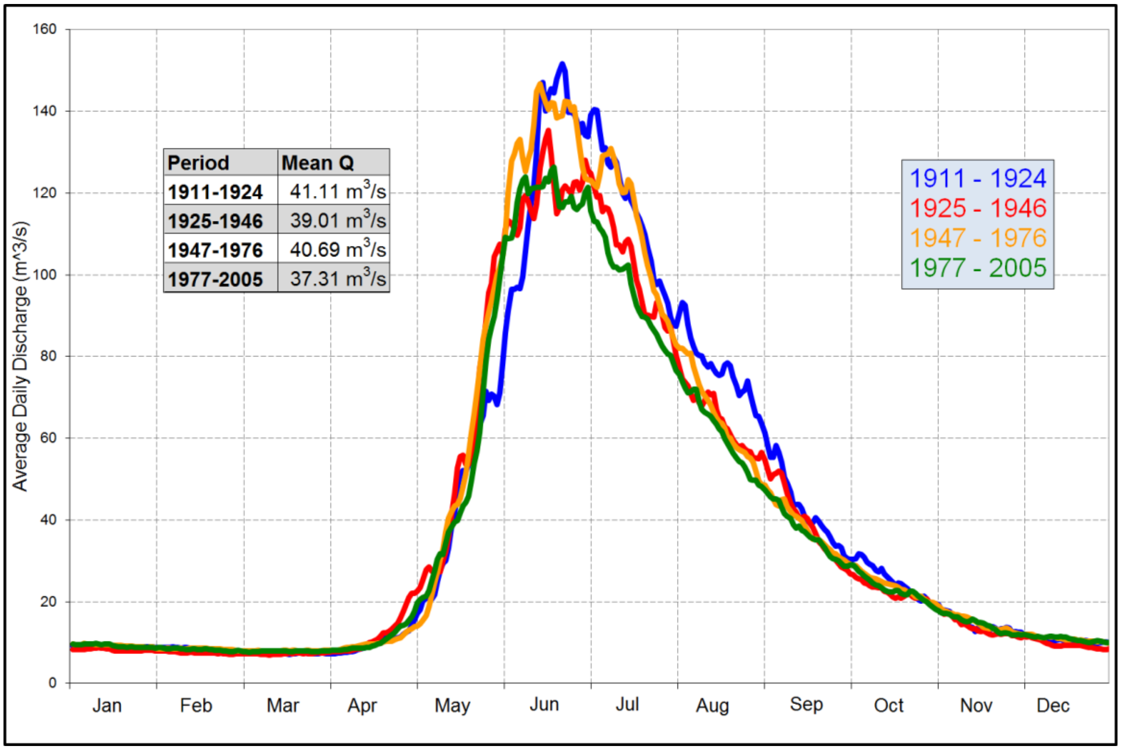
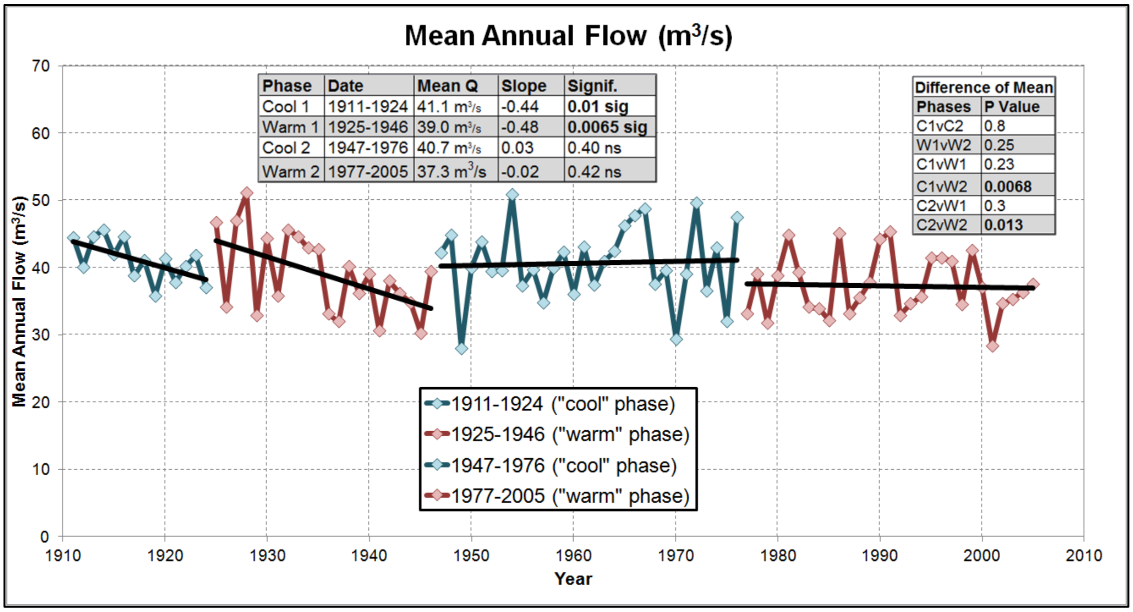


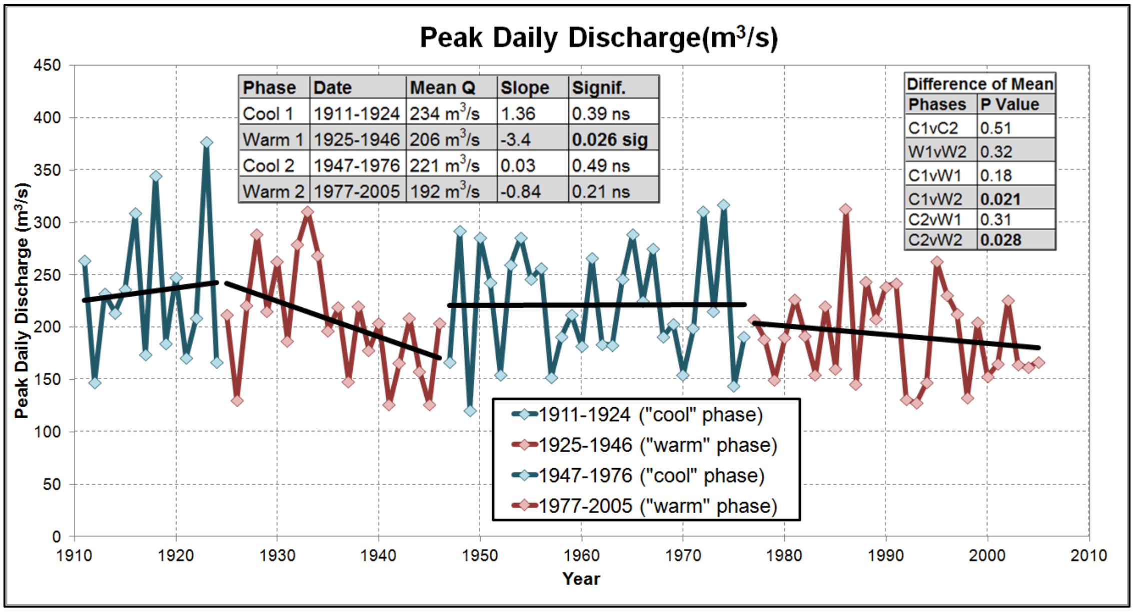
Figure 3.26: Average daily discharge for the four PDO phases for the Bow River at Banff.



Phase	Date	Mean Q	Slope	Signif.
Cool 1	1911-1924	41.1 m^3/s	-0.44	**0.01 sig**
Warm 1	1925-1946	39.0 m^3/s	-0.48	**0.0065 sig**
Cool 2	1947-1976	40.7 m^3/s	0.03	0.40 ns
Warm 2	1977-2005	37.3 m^3/s	-0.02	0.42 ns

Difference of Mean	
Phases	P Value
C1vC2	0.8
W1vW2	0.25
C1vW1	0.23
C1vW2	**0.0068**
C2vW1	0.3
C2vW2	**0.013**

Figure 3.27: Mean annual flow of the Bow River at Banff categorized by PDO phase. P values are between differences in means determined using a t-test, bold relationships are significant.

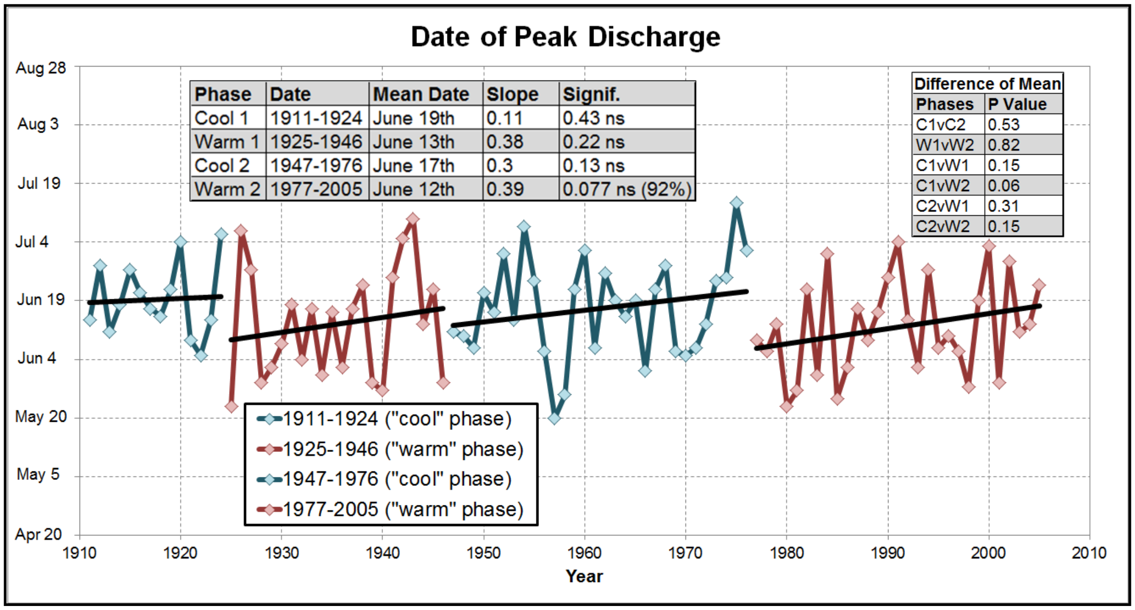


Phase	Date	Mean Q	Slope	Signif.
Cool 1	1911-1924	234 m^3/s	1.36	0.39 ns
Warm 1	1925-1946	206 m^3/s	-3.4	**0.026 sig**
Cool 2	1947-1976	221 m^3/s	0.03	0.49 ns
Warm 2	1977-2005	192 m^3/s	-0.84	0.21 ns

Difference of Mean	
Phases	P Value
C1vC2	0.51
W1vW2	0.32
C1vW1	0.18
C1vW2	**0.021**
C2vW1	0.31
C2vW2	**0.028**

Figure 3.28: Peak daily discharge of the Bow River at Banff categorized by PDO phase. P values are between differences in means determined using a t-test, bold relationships are significant.

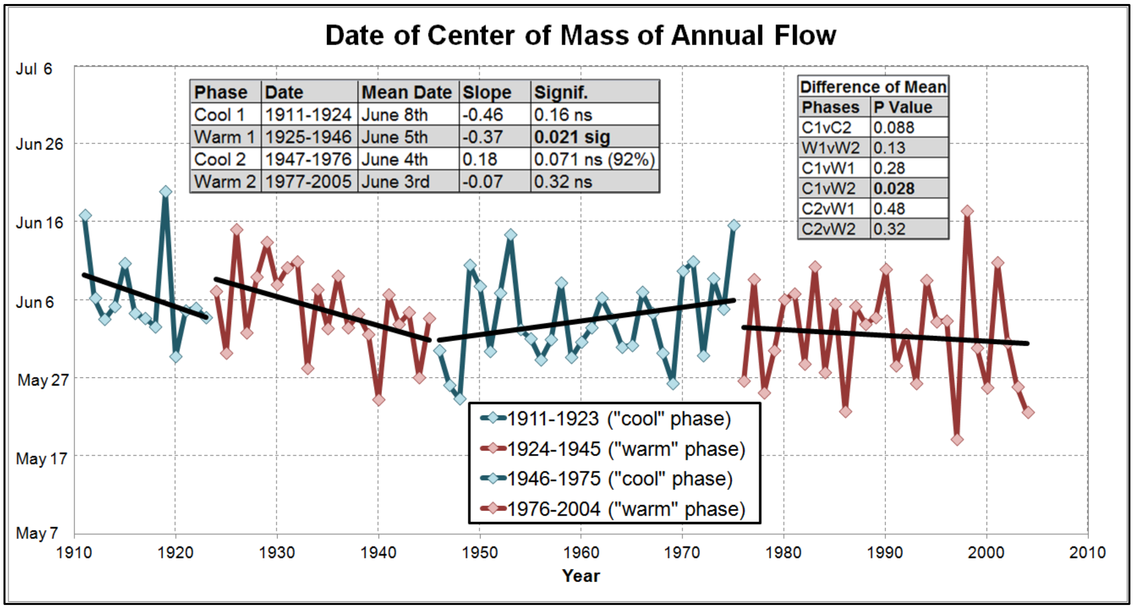
individual "phases" show differing patterns (Figure 3.28). The post-1976 peak discharges are significantly lower than both the "cool" PDO phases. Mean flow volumes in the 1925-1946 "warm" phase are not significantly different but it is the only period with strong and significant decreasing trend. The 1911-2005 record shows a non-significant trend in date of peak discharge suggesting a peak ca. three days earlier over the period of record (results not shown, $r^2 = 0.26$ ns). However all four PDO phases show positive trends (later dates for peak discharge, Figure 3.29) though none are significant and only the 1911-24 and 1977-2005 periods have significantly different means (peaks in the post 1976 period are on average seven days earlier). The trends in CT show an earlier timing of flows for the entire record (Figure 3.7) and for three of the four phases (Figure 3.30), though only the 1925-1946 trend is significant. The earlier "cool" phase has a stronger negative trend but the smaller sample and late 1919 event (the latest in the record) result in a non-significant result. In contrast the 1947-1976 "cool" phase has a positive though marginally non-significant trend. The mean CT dates for the three latter phases are similar and, though the two "warm" phases show earlier dates, only the dates between the 1911-1924 (June 8th) and the post 1976 period (June 2nd) are significantly different. These analyses indicate that there are considerable differences in streamflow regime associated



Phase	Date	Mean Date	Slope	Signif.
Cool 1	1911-1924	June 19th	0.11	0.43 ns
Warm 1	1925-1946	June 13th	0.38	0.22 ns
Cool 2	1947-1976	June 17th	0.3	0.13 ns
Warm 2	1977-2005	June 12th	0.39	0.077 ns (92%)

Difference of Mean	
Phases	P Value
C1vC2	0.53
W1vW2	0.82
C1vW1	0.15
C1vW2	0.06
C2vW1	0.31
C2vW2	0.15

Figure 3.29: Date of peak discharge of the Bow River at Banff categorized by PDO phase. P values are between differences in means determined using a t-test.



Phase	Date	Mean Date	Slope	Signif.
Cool 1	1911-1924	June 8th	-0.46	0.16 ns
Warm 1	1925-1946	June 5th	-0.37	**0.021 sig**
Cool 2	1947-1976	June 4th	0.18	0.071 ns (92%)
Warm 2	1977-2005	June 3rd	-0.07	0.32 ns

Difference of Mean	
Phases	P Value
C1vC2	0.088
W1vW2	0.13
C1vW1	0.28
C1vW2	**0.028**
C2vW1	0.48
C2vW2	0.32

Figure 3.30: CT date of the Bow River at Banff categorized by PDO phase. P values are between differences in means determined using a t-test, bold relationships are significant.

with phase shifts of the PDO, particularly post 1976, that are masked in any linear analyses of the entire record. The timing of peak discharge is especially variable but all four measures show substantial influence from the PDO. The trends in the 1947-1976 “cool” period are masked in the linear analysis of the entire record by data from the two strong “warm” phases flanking this 30 year period. This demonstrates the importance of examining and understanding the potential influence of decadal and multidecadal variability before interpreting linear trends from long hydroclimate records.

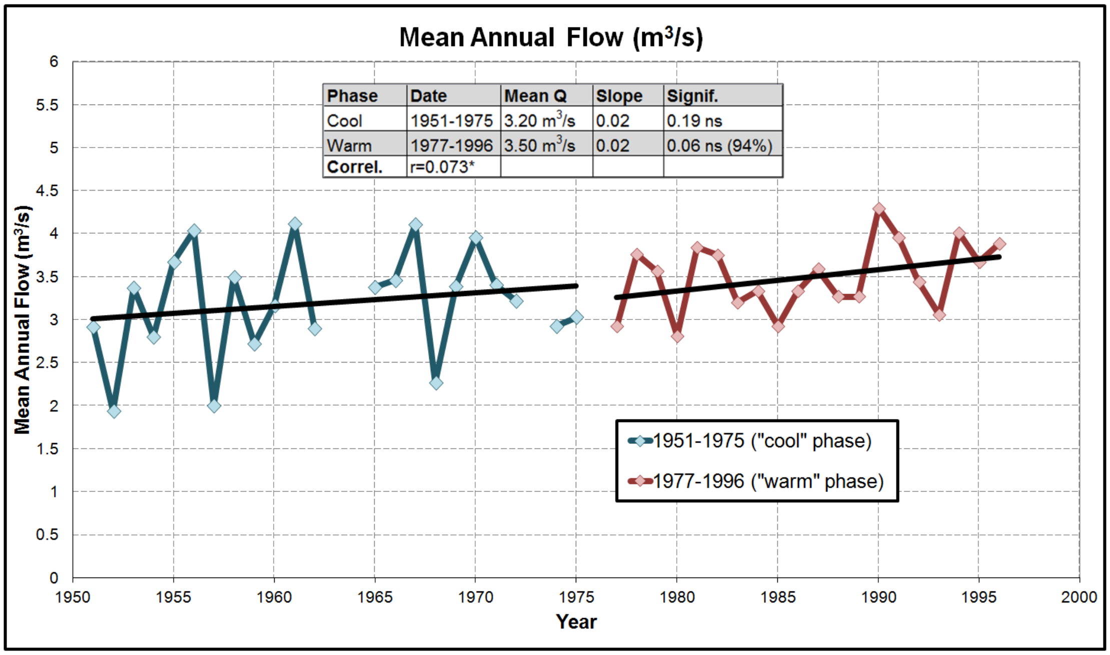
3.7.2 The Sunwapta Record

The gauge record for the Sunwapta River at Athabasca Glacier potentially has adequate data to explore differences in streamflow characteristics on either side of the 1976 PDO shift. Table 3.7 and Figures 3.31-3.34 show analysis of these data subdivided into the “cool” phase (1951-1975, missing data for 1963, 64, and 73) and the “warm” phase (1977-1996). Mean annual flows are higher post 1976 ($3.50m^3/s$ vs. $3.20m^3/s$) and almost significantly different (94% confidence level) but the two phases appear to show significantly different variances (correlation = 0.073, Figure 3.31) possibly related to the greater variability of the pre 1976 record. Nevertheless both periods show positive, though non-significant trends in streamflow volumes. The volume and dates of peak discharge (Figures 3.32-3.33) have been corrected for the fall rainfall events. The peak daily discharge for the "warm" phase has a statistically significant increasing trend although the earlier "cool" period shows almost no trend. However, the mean peak daily discharge values for the two periods are quite similar (8.56m^3/s and 8.68m^3/s) and the variance of peak daily discharge values between the two phases is strongly related (correlation= 0.83) that the two series are not as different as the slopes and statistical tests show but are being influenced by the large range of values within each phase of record.

Table 3.7: Sunwapta River at Athabasca Glacier mean values for the PDO phases through the 20th century. Corrected peak values are used in this analysis.

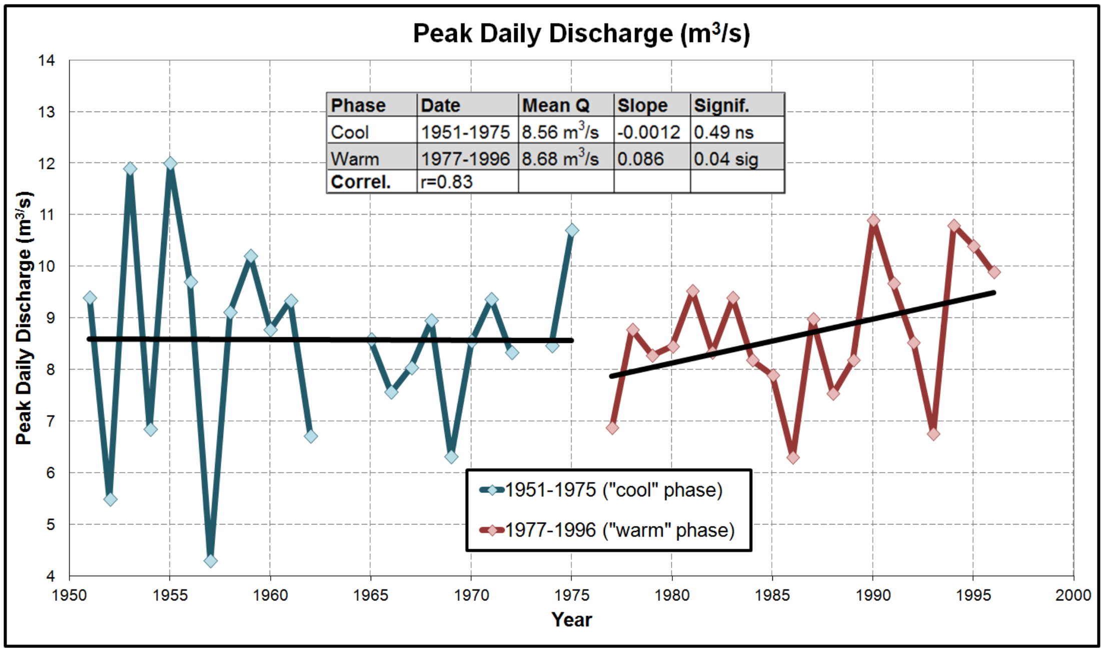
PDO phase	*Mean Annual Flow (m^3/s)*	*Peak Daily Discharge (m^3/s)*	*Peak Date*	*CT date*
"Cool" 1951-1975	3.20	8.56	July 28	July 30
"Warm" 1977-1996	3.50	8.68*	July 29	July 28

* Trends over this period are significant



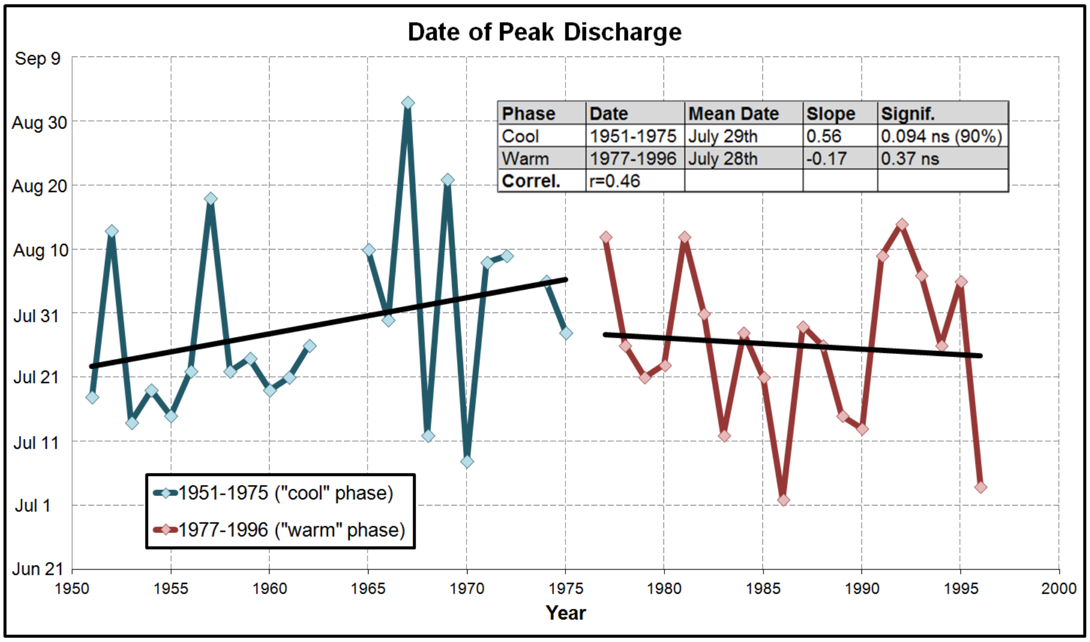
Phase	Date	Mean Q	Slope	Signif.
Cool	1951-1975	3.20 m^3/s	0.02	0.19 ns
Warm	1977-1996	3.50 m^3/s	0.02	0.06 ns (94%)
Correl.	r=0.073*			

Figure 3.31: Mean June 1 – September 30 flow of the Sunwapta River at Athabasca Glacier categorized by PDO phase. Correlation is between differences in means, * denotes a significant correlation.



Phase	Date	Mean Q	Slope	Signif.
Cool	1951-1975	8.56 m^3/s	-0.0012	0.49 ns
Warm	1977-1996	8.68 m^3/s	0.086	0.04 sig
Correl.	r=0.83			

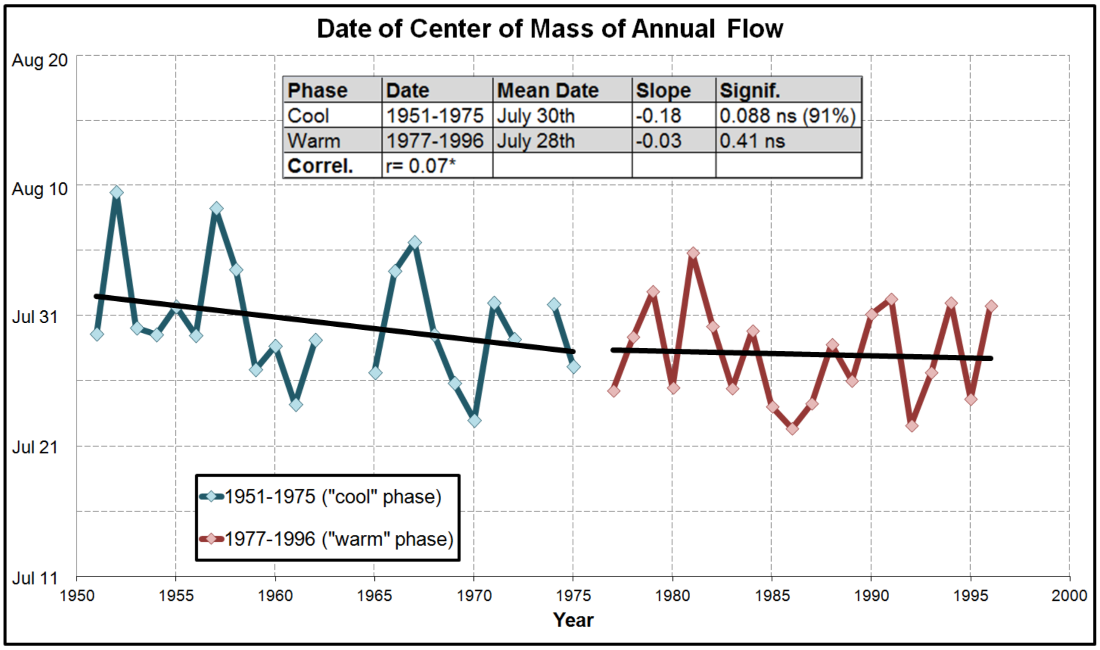
Figure 3.32: Peak daily discharge between June 1 – September 30 of the Sunwapta River at Athabasca Glacier categorized by PDO phase. Corrected peak discharge values are used in this analysis. Correlation is between differences in means.



Phase	Date	Mean Date	Slope	Signif.
Cool	1951-1975	July 29th	0.56	0.094 ns (90%)
Warm	1977-1996	July 28th	-0.17	0.37 ns
Correl.	r=0.46			

Figure 3.33: Date of peak discharge between June 1 and September 30 for Sunwapta River at Athabasca Glacier categorized by PDO phase. Corrected peak dates are used in this analysis. Correlation is between differences in means.

The mean date of peak discharge is similar (July 28th – July 29th, Figure 3.33) between the two periods although there is considerable range in dates and the overall trends differ, becoming later in the earlier period and earlier in the later period. Conversely the CT data show a strong trend to earlier streamflow in the 1951-75 interval but little trend after the 1976 shift (Figure 3.34). The mean date of the later, “warm” phase is two days earlier than the “cool” phase (28th:30th July). In summary, the mean annual flow and CT data show differences between the two PDO phases though the peak daily discharge data are too variable to be statistically significant. These data indicate that the PDO has some effects on discharge in this record but a longer, more complete record is needed to provide a definitive statement. The differences between the Bow and Sunwapta PDO analyses suggest that the overall trends on the proglacial record of Sunwapta are not as highly correlated to the PDO. However, this could be an artifact of using truncated streamflow records that remove the potential influence of early (May) discharge events or a reflection of the short, incomplete record.



Phase	Date	Mean Date	Slope	Signif.
Cool	1951-1975	July 30th	-0.18	0.088 ns (91%)
Warm	1977-1996	July 28th	-0.03	0.41 ns
Correl.	r= 0.07*			

Figure 3.34: CT date for the June 1 – September 30 period of the Sunwapta River at Athabasca Glacier categorized by PDO phase. Correlation is between differences in means, * denotes a significant correlation.

The evidence presented above indicates that changes in the streamflow patterns appear to be related to phase changes in the PDO. These changes can be most clearly seen in the long Bow streamflow record. Although records are not adequate to demonstrate similar effects in the Athabasca record, examination of differences in the results of analyses between the 1971-2005 and 1977-2005 periods (e.g. in Figures 3.5-3.7) indicate streamflows were likely greater prior to the 1976 shift.

3.7.3 Athabasca and Miette Records

The Athabasca record does not have sufficient data to run a quantitative trend analysis on the PDO phases. However, when looking at the "cool 1" phase (data for 1914-1921 and 1924) and the "cool 2" phase (data for 1971-1976) it can be seen that the volumes of streamflow are greater and the timing of streamflow is occurring later in the year than the "warm 2" phase (1977-2005). The data from the Miette River are even scarcer with only one year of data existing for the "cool 2" phase (1976). However, the earlier "cool 1" phase has data for 1915-1920 and it also shows later streamflow timing and streamflow volumes that are larger than those during the "warm 2" (1977-2005) phase.

3.8 Conclusion

The analyses performed in this chapter demonstrate the hydrologic variability in 20th century streamflow records from the southern Canadian Cordillera. The long, continuous Bow record and the data available for the Athabasca River near Jasper demonstrate that over the 20th century streamflow volumes have decreased and timing of the centre of mass of flow (CT) is moving earlier in the year. The Athabasca and Miette comparison showed some minor differences in the records related to the contribution of glacial melt that is reflected more in the timing and magnitude of the events each year rather than the overall trends and patterns. The Sunwapta River analysis demonstrated that, while the earlier CT timing is common to all basins, the glacial effect in this record is reflected in contribution of streamflow seen later in the season which relates to melt on the Athabasca Glacier.

Although they are different in size, comparison of median flow dates and annual hydrographs indicate that the Bow River and Athabasca River are demonstrating that the pattern of discharge on these two rivers is similar. This indicates the potential for the Bow record to be a surrogate for the missing portion of the Athabasca record but an analysis of how they are affected by climate variations needs to be undertaken before this can be determined definitively. One pattern that is clearly visible in this work is that of the Miette River near Jasper and the Athabasca River above Jasper showing different timing of streamflow. The lack of glacial inputs on the Miette River is causing higher streamflow values to occur earlier in the year with a transition to baseflow conditions occurring earlier in the fall than on the Athabasca. This and the difference in patterns observed between the Sunwapta River and the four other records studied indicates that glacial cover does affect streamflow timing in the study basin.

The analyses confirm significant effects of the Pacific Decadal Oscillation (PDO) on changes in the volume and timing of streamflow in the Bow record between the "cool" and "warm" phases over the 20th century. The patterns observed for the mean annual flow, peak daily discharge, and CT date within these phases differ from the overall trends for the 1911-2005 period and complicate the interpretation of linear analysis of this long term record. Analysis of the seasonal Sunwapta River data did not show as strong a difference in pattern as the Bow but the 1976 shift is also marked in these data. These analyses indicate there is considerable decadal and possibly multidecadal variability in the hydrological records of this region that must be evaluated and understood before interpreting possible long term trends from these data. Further analyses of these data and their relationship to climate records will be evaluated in subsequent chapters.

Chapter 4

4 Comparison of the observed hydrological trends in the southern Canadian Cordillera to proximal climate records

4.1 Introduction

The previous chapter has discussed hydrological trends in the streamflow records of the southern Canadian Cordillera, noting relationships between discharge patterns, glacier cover and the PDO. The current chapter explores the relationships between discharge and the more conventional climate variables of precipitation and temperature and specifically how these changes are manifested in the PDO. Stewart *et al* (2005) considered temperature change was the dominant factor in hydrological change in high alpine basins in western North America noting that such changes are more pronounced in mountain environments (Beniston, 2005, Rood *et al*, 2005). Demuth and Pietroniro (2003) report that the glacier-derived discharge in the North Saskatchewan River basin are already experiencing major modifications related to increasing temperatures and variations in regional precipitation. In addition, several authors note the important control of the PDO that is manifested by changes in both temperature and precipitation in western North America (Moore & McKendry, 1996, Hamlet *et al*, 2005, Stewart *et al*, 2005, Gobena & Gan, 2006, Demuth *et al*, 2008) This chapter will discuss relationships between the hydrological trends observed in the Bow, Athabasca and Sunwapta Rivers with instrumental precipitation and temperature records from Banff and Jasper.

4.2 Data sources

Most large scale studies linking streamflow and climate in western North America have used multiple sites and gridded climate anomaly data to compare these variables (Hamlet & Lettenmaier, 1999, Stewart *et al*, 2004, 2005, Hamlet *et al*, 2005, Shepherd *et al*, 2010). The grid squares that are usually 5° longitude by 5 or 10° latitude (Luckman & Seed, 1995) are too large to be appropriate for a localized study, especially in the case of precipitation which can be spatially quite variable. In the present study the objective was to compare local hydrological trends to local climate variations. Therefore direct comparisons were made with station records from Environment Canada's Historical Climate Data Network. This network provides the only long term climate records for the high elevation areas of the Canadian Rockies. Their stations at Banff and Jasper were selected for comparison to the selected hydrological sites. The data from Banff begins in 1887 and the data from 1909 until 2005 are used. The station location was moved a few meters in 1985 and the records from the two stations (Banff and Banff CS) are merged. The data for Jasper comes from three locations. The first location (Jasper 1) operated from 1914 to 1931 and the second (Jasper 2) from 1926-1994. In this analysis data from 1914-1927 and 1929-1930 come from Jasper 1 and 1928 and 1931-1994 data come from Jasper 2, using the station with the most complete record from the years where there was overlap. From January 1, 1995 the station was moved a short distance to the 'Jasper Warden' location which provides the record from 1995-2005. Gaps in the precipitation data for the Jasper Warden record are filled using data from the 'Jasper East Gate' station. The three Jasper stations are located in similar surroundings and not far from each other, so no adjustments have been made to the merged data sets. Previous analysis of these climate records by Luckman and Seed (1995) indicated that differences in the records from Jasper 1 and 2 were insignificant with only minor changes of exposure of the instruments.

Parameters of daily mean, maximum, and minimum temperatures along with daily rainfall, snowfall, and total precipitation were used from the above sources. Only years with 95% of days with data were used for the climate analysis which was determined parameter by parameter (removing two-four years based on the parameter). Calendar years with a few missing data (one or two days) were included as verification trials, indicated the missing data had little impact on the annual or seasonal values. The daily temperature data were summed and averaged to create annual and seasonal databases for mean, maximum, and minimum temperatures. The daily precipitation values were aggregated to provide annual and seasonal rainfall, snowfall, and precipitation records. The winter season used in this study is defined as November through to March. This period was chosen as these five months are those in which the mean daily temperatures average was below zero in the 1911-2005 period allowing for snowfall to occur. Seasons with < 95% of daily data were omitted (removing three-six years based on the parameter). The remaining years had 100% daily data (there were no years with between 0 and 5% missing data).

4.3 Relationships between discharge of the Bow River at Banff and Banff climate record

4.3.1 Previous work

Several papers have examined climate records in the Canadian Rockies noting some consistent trends in the region (Luckman & Seed, 1995, Luckman, 1998, Watson & Luckman 2005b, Watson *et al*, 2008). Luckman (1998) identified three meteorological stations that provide long term records from the southern Canadian Cordillera, namely Banff, Jasper and Lake Louise. The Banff record is the longest beginning in 1887 and having continuous data from 1890 to the present (Luckman & Seed, 1995). Based on this long, continuous Banff climate record the following observations have been made: 1) the record (along with others in the region) shows decadal scale anomalies of temperature and precipitation data. These are similar to phases of the PDO which had not been identified at that time (Luckman, 1998); 2) there are strong differences in the range and trends of seasonal temperature data (also seen in the regional record, Watson *et al*, 2008); and, 3) more than half of the annual precipitation at Banff occurs between April and August (Watson & Luckman, 2005b). Watson and Luckman (2005b) also noted the correlation between PDO and annual discharge of the Bow and developed a 300 year long reconstruction of Bow River streamflow based on the relationship between Douglas Fir ring widths, Peyto winter mass balance and winter precipitation in Banff (see Figure 4 in Watson & Luckman, 2005b). With these observed trends in the climate variables already identified one would expect that streamflow of the Bow River at Banff would be related to these variables.

In his study of regional temperature records from the Canadian Rockies Luckman (1998, Luckman & Kavanagh, 2000) showed that mean annual temperatures increased 1.4°C over the 1888-1994 period but showed strong seasonal differences. Seasonal increases were 1.3°C / century for spring (April-June) and summer (July – September), 3.2°C/century for winter (January – March) and no trend (0.07°C/century) was observed for fall (October – December). There were also considerable differences in the interannual range between 3.8°C in summer (JJA, 4.51°C for JAS) and 12.7°C in winter (JFM). Streamflow throughout western North America has been shown to be strongly related to winter climate parameters (Stewart *et al*, 2005, Mote, 2006, Demuth *et al*, 2008) and winter temperature increases have been linked to a decrease in glacial cover (Moore *et al*, 2009). Watson and Luckman (2005b) found that the Peyto Glacier record is well correlated with Bow river streamflow. Luckman (1998) also reports a significant correlation (r=0.59) between annual Bow River streamflow and annual (water year) precipitation at Banff for the 1911-1994 period. As precipitation is found to be quite variable over the entire southern Canadian Cordillera (Luckman, 1998, Luckman & Kavanagh, 2000) the Jasper and Banff records were considered the best available for analysis. The Lake Louise record was not used because the Jasper and Banff precipitation records were more complete for the period of hydrological comparison. Although 76% of annual Bow streamflow and 54% of Banff precipitation occur between April and August, these two variables are poorly correlated; summer streamflow correlates most strongly with winter precipitation and winter mass balance records from Peyto Glacier (Watson & Luckman, 2005b). Therefore it is important to compare the long term Bow River trends to both the annual and winter climate records.

The annual temperature data from 1911-2005 at Banff (Figure 4.1) show the warming trend seen in previous studies. However, minimum temperatures in this record are increasing at a greater rate than the maximum and mean temperatures, as also noted by Wilson and Luckman (2003) and Watson *et al* (2008). The annual trends for the mean and minimum temperatures are statistically significant but the lower trend for maximum temperature is not. The trend in the mean winter temperature (November – March, Figure 4.2) is significant and the change in values is larger than the mean annual temperature though the winter pattern is quite variable with an absolute range of 7.9°C. This matches Luckman's (1998) observation that the winter signal is the primary control on interannual variation in temperature. Minimum temperatures (Figure 4.3) also show greater changes in the winter with a significant positive trend and a greater range (8.3°C) than the annual minimum (5.3°C).

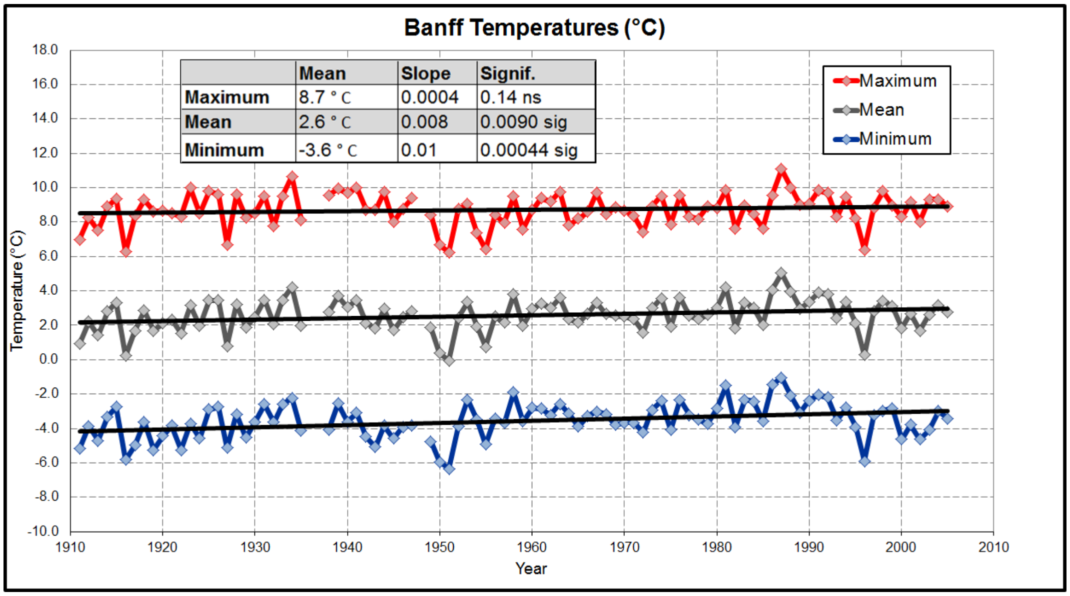


Figure 4.1: Mean, maximum, and minimum temperature trends for Banff from 1911-2005.

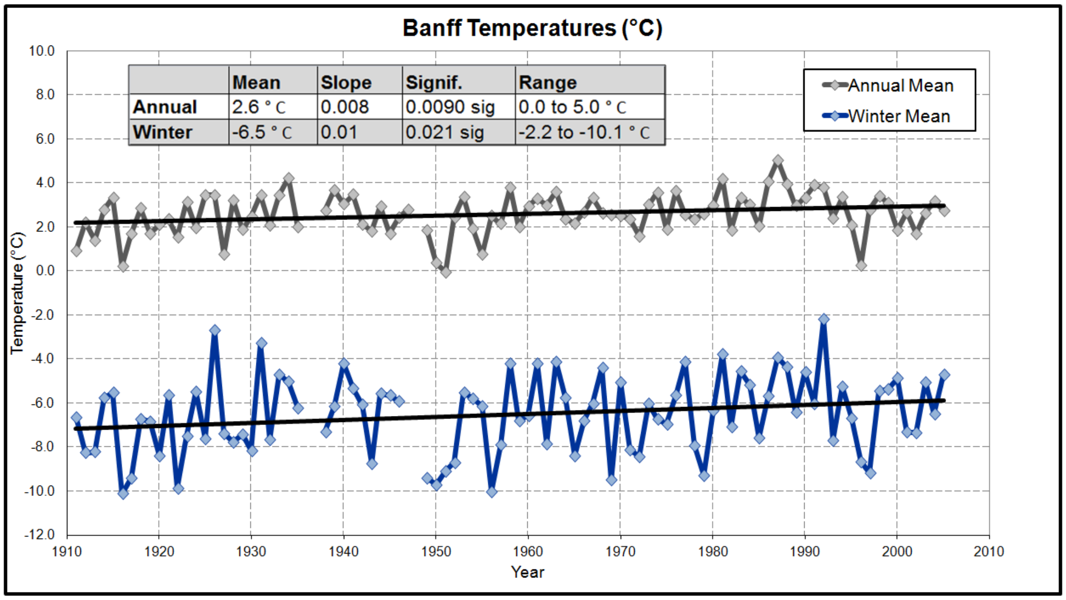
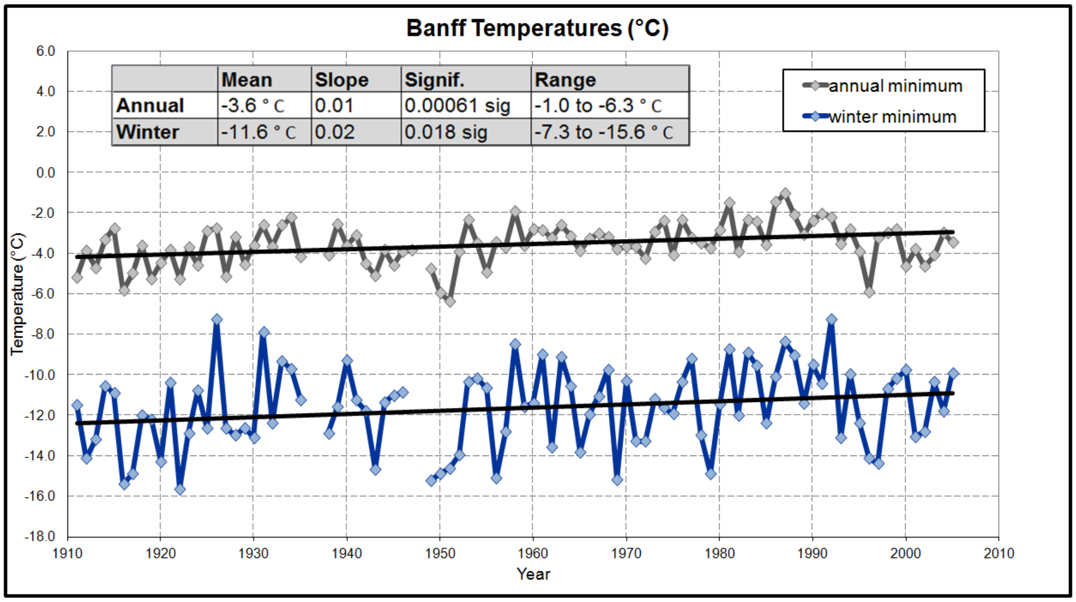


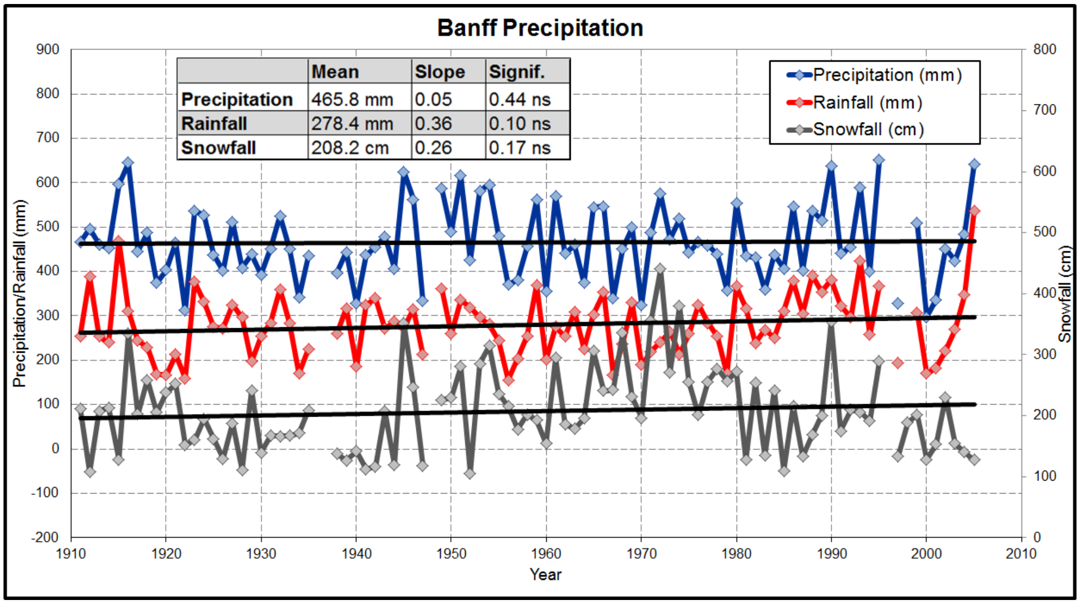
Figure 4.2: Mean annual and mean winter temperature trends for Banff from 1911-2005.

The annual trends for precipitation show a minor but statistically insignificant increase over the entire record (Figure 4.4). The snowfall data are highly variable with strong decadal scale variation (related to the PDO) and a weakly positive trend. Snowfall provides on average 42.6% of the Banff precipitation record and is therefore an important contributor to water availability.



	Mean	Slope	Signif.	Range
Annual	-3.6 ° C	0.01	0.00061 sig	-1.0 to -6.3 ° C
Winter	-11.6 ° C	0.02	0.018 sig	-7.3 to -15.6 ° C

Figure 4.3: Minimum annual and minimum winter temperature trends for Banff from 1911-2005.

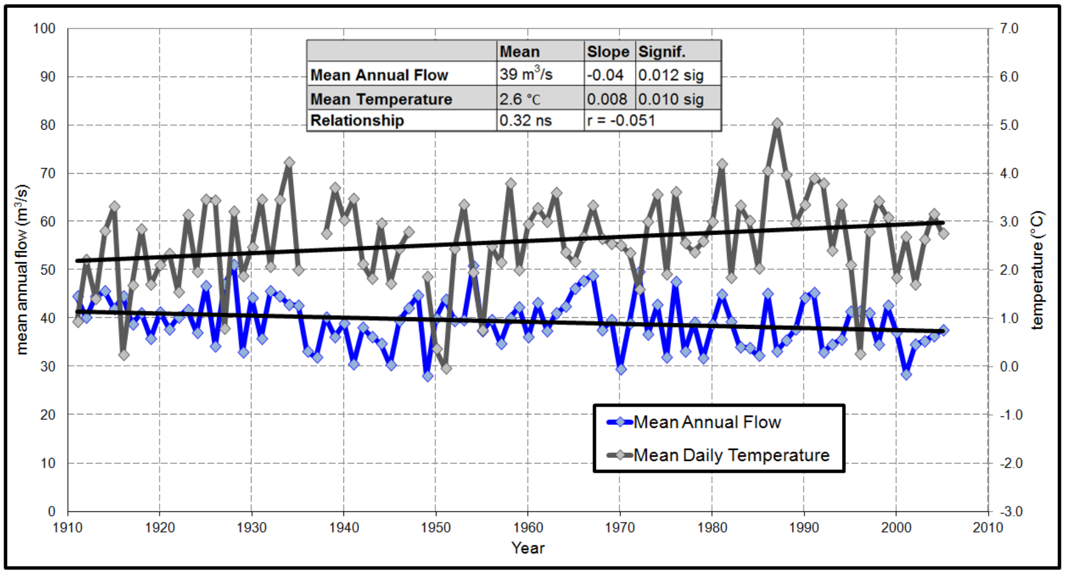


	Mean	Slope	Signif.
Precipitation	465.8 mm	0.05	0.44 ns
Rainfall	278.4 mm	0.36	0.10 ns
Snowfall	208.2 cm	0.26	0.17 ns

Figure 4.4: Rainfall, snowfall, and combined precipitation trends for Banff from 1911-2005.

4.3.2 Relationships between discharge and climate variables

Initial analyses were carried out comparing annual climate records to mean annual flow values and CT dates. Both the mean annual flow and CT date were found to have significant negative trends over the 1911-2005 period whereas mean annual temperatures have a positive trend (Figures 4.5 and 4.6). While there clearly appears to be a linkage between mean temperatures and these hydrological variables the relationship between them is not significant (r = 0.32 and 0.40) over this time period. However, since winter climate parameters are known to affect streamflow the trends in mean annual flow and CT date were compared to the mean winter (November through March) temperatures and snowfall (Figures 4.7 through 4.9). These temperature relationships were found to be stronger than those with the annual temperatures though they remained non-significant. The strongest relationship however was seen between mean annual flow and winter snowfall (significant at the 99% confidence level, there was no relationship between CT and winter snowfall). The winter snowfall data does not show a significant trend itself but the variability in the precipitation values are clearly linked to the changes in Bow streamflow magnitude. The increased winter temperatures result in later initiation and greater melt along with earlier snowmelt contribution which could explain the earlier CT



	Mean	Slope	Signif.
Mean Annual Flow	39 m^3/s	-0.04	0.012 sig
Mean Temperature	2.6 °C	0.008	0.010 sig
Relationship	0.32 ns	r = -0.051	

Figure 4.5: Bow River at Banff mean annual flow and Banff mean temperature for the period of 1911-2005. Correlation is between the annual values.

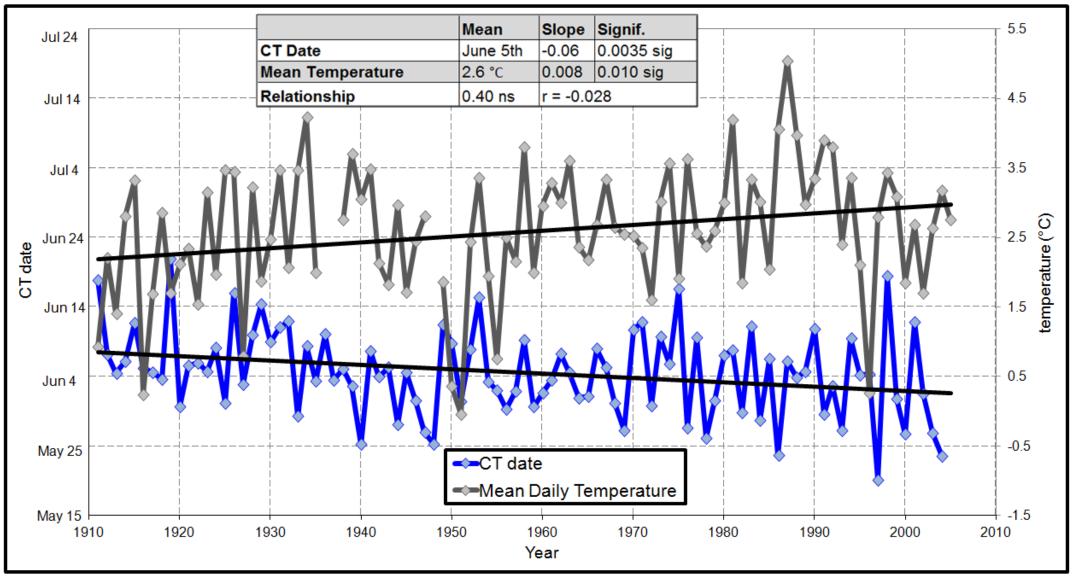


Figure 4.6: Bow River at Banff CT date and Banff mean temperature for the period of 1911-2005. Correlation is between the annual values.

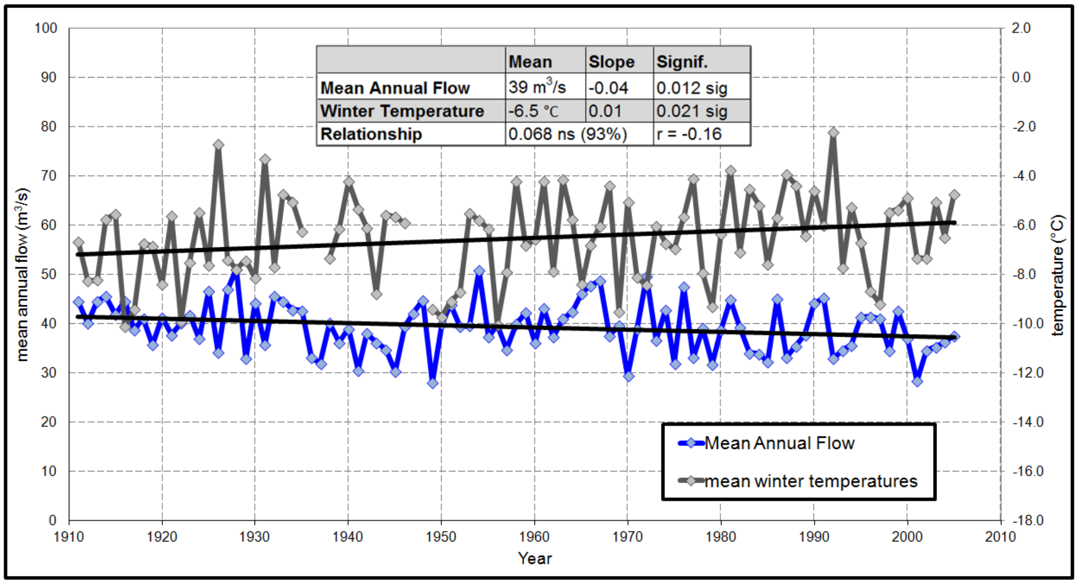
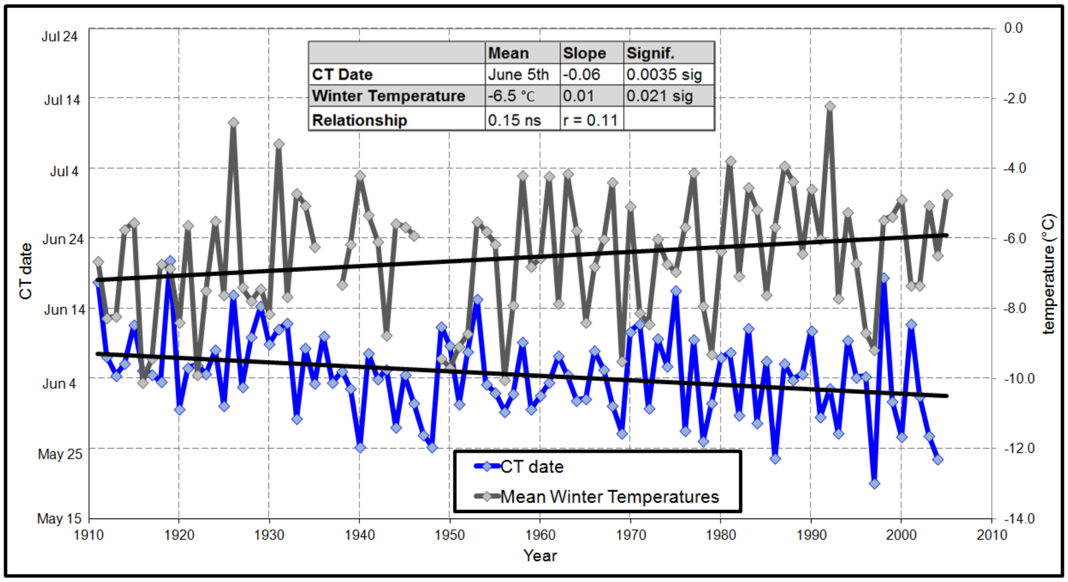


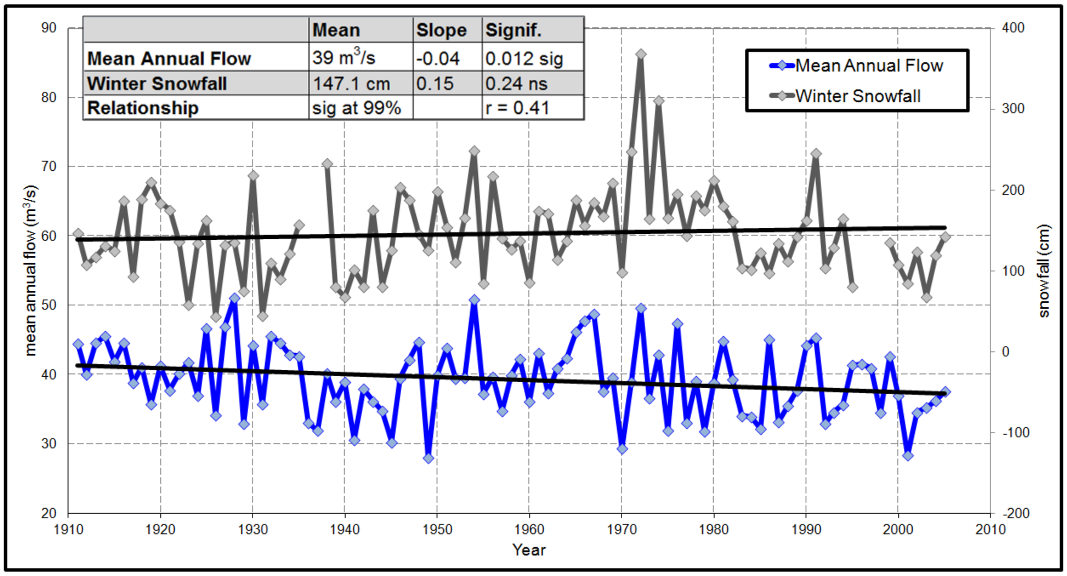
Figure 4.7: Bow River at Banff mean annual flow and Banff mean winter temperature for the period of 1911-2005. Correlation is between the annual values.

dates unless it was accompanied by an increase in late summer/early fall precipitation which would offset the earlier melt contribution. However, June- September precipitation at Banff shows little trend over the 20th century record (Figure 4.10), demonstrating that there is not a precipitation offset allowing the assumption of a earlier and greater melt contribution to stand as the cause of the CT timing trend.



	Mean	Slope	Signif.
CT Date	June 5th	-0.06	0.0035 sig
Winter Temperature	-6.5 °C	0.01	0.021 sig
Relationship	0.15 ns	r = 0.11	

Figure 4.8: Bow River at Banff CT date and Banff mean winter temperature for the period of 1911-2005. Correlation is between the annual values.



	Mean	Slope	Signif.
Mean Annual Flow	39 m^3/s	-0.04	0.012 sig
Winter Snowfall	147.1 cm	0.15	0.24 ns
Relationship	sig at 99%		r = 0.41

Figure 4.9: Bow River at Banff mean annual flow and Banff winter snowfall for the period of 1911-2005. Correlation is between the annual values.

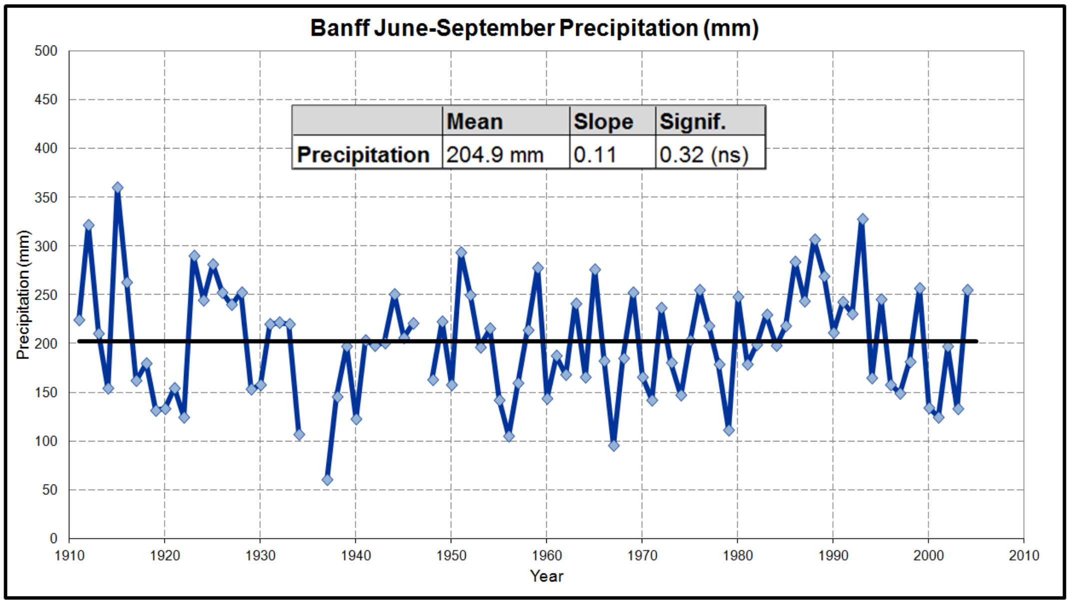
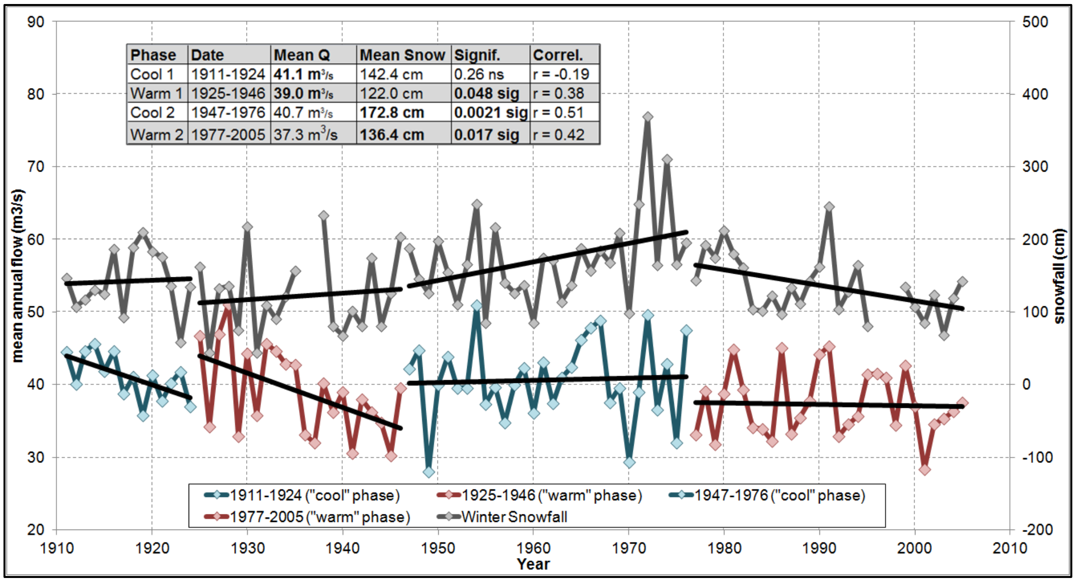


Figure 4.10: June through September precipitation trends for Banff from 1911-2005.

As was observed in previous studies of climate in the Canadian Rockies, the major pattern observed is decadal scale changes in the climate variables (Luckman & Seed, 1995, Luckman, 1998, Luckman & Kavanagh, 2000, Watson *et al*, 2008). Based on the work done by Mantua *et al*, 1997 we would assume that this decadal scale pattern is related to the PDO. The PDO has also been found to affect streamflow in many studies in western North America (Moore & McKendry, 1996, Hamlet *et al*., 2005, Stewart *et al*, 2005, and Gobena & Gan, 2006). Moore *et al* (2009) indicate the most prominent effects of the PDO are found in the winter months and are specifically linked to variations in winter precipitation, wintertime air temperature, snowpack, and glacial mass balance records (Mantua *et al*, 1997, Selkowitz *et al*, 2002, Munro, 2005, Watson & Luckman, 2005a, Mote, 2006, Watson & Luckman, 2006, Demuth *et al*, 2008, Moore *et al*, 2009). Therefore selected variables in the Banff climate records were examined with relation to the four 20th century phases of the PDO.

Based on the fact that the best climate relationship matched to mean annual flow was winter snowfall (Figure 4.11) it could be assumed that this parameter would also have a strong connection to mean annual flow when broken into the PDO phases. As expected,

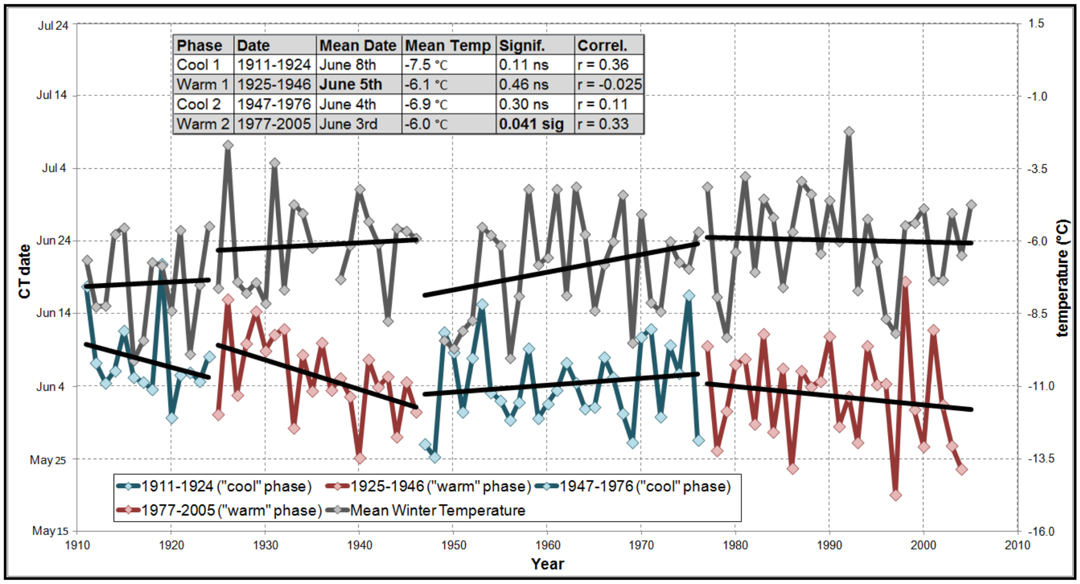


Phase	Date	Mean Q	Mean Snow	Signif.	Correl.
Cool 1	1911-1924	**41.1 m^3/s**	142.4 cm	0.26 ns	r = -0.19
Warm 1	1925-1946	**39.0 m^3/s**	122.0 cm	**0.048 sig**	r = 0.38
Cool 2	1947-1976	40.7 m^3/s	**172.8 cm**	**0.0021 sig**	r = 0.51
Warm 2	1977-2005	37.3 m^3/s	**136.4 cm**	**0.017 sig**	r = 0.42

Figure 4.11: Mean annual flow for the Bow River and winter snowfall at Banff for 1911-2005 broken into the PDO phases. Chart entries in bold indicate a significant relationship between the mean annual flow and winter snowfall for that phase. Black lines represent trends through each PDO phase for each variable. Correlation is between the annual values.

mean annual flows do show significant relationships to winter snowfall (Figure 4.11) for the "warm 1" (r=0.38, p=0.048), "cool 2" (r=0.51, p= 0.0021), and "warm 2" (r= 0.42, p=0.017) phases. The 1911-1924 "cool" phase does not show a relationship between these two variables. Both mean winter snowfall and annual flows are lower during the two "warm" phases and higher during the "cool" phases, these relationships are significant for all instances involving "cool 2" phase but not for instances involving "cool 1" phase. This confirms that winter precipitation, via spring melt is the major control of spring-summer and annual streamflows. There is also a link between peak discharge volume and winter snowfall (data not shown) though it is harder to justify a comparison between a daily discharge measure to a seasonal total. Nevertheless the volume of snowpack available in the system dictates the magnitude of both peak and annual flows.

The long term relationship seen between Bow River CT date and Banff mean annual temperatures suggests that there may also be a relationship between these variables within individual PDO phases. However, for individual PDO phases the only temperature variable to have a significant relationship with CT date was the mean winter temperatures (Figure 4.12) during the 1977-2005 “cool” phase (r=0.33, p=0.041). Moreover there are no significant relationships between CT date and winter snowfall although both variables often show similar trends (Figure 4.13). The higher winter temperatures and lower winter snowfalls during the two “warm” phases could relate to the observed trends of earlier CT date during these periods. The 1947-1976 “cool” phase had the opposite conditions occurring with lower winter temperatures and higher winter snowfalls. Once again the 1911-1924 “cool” phase does not show clear relationships between these variables.



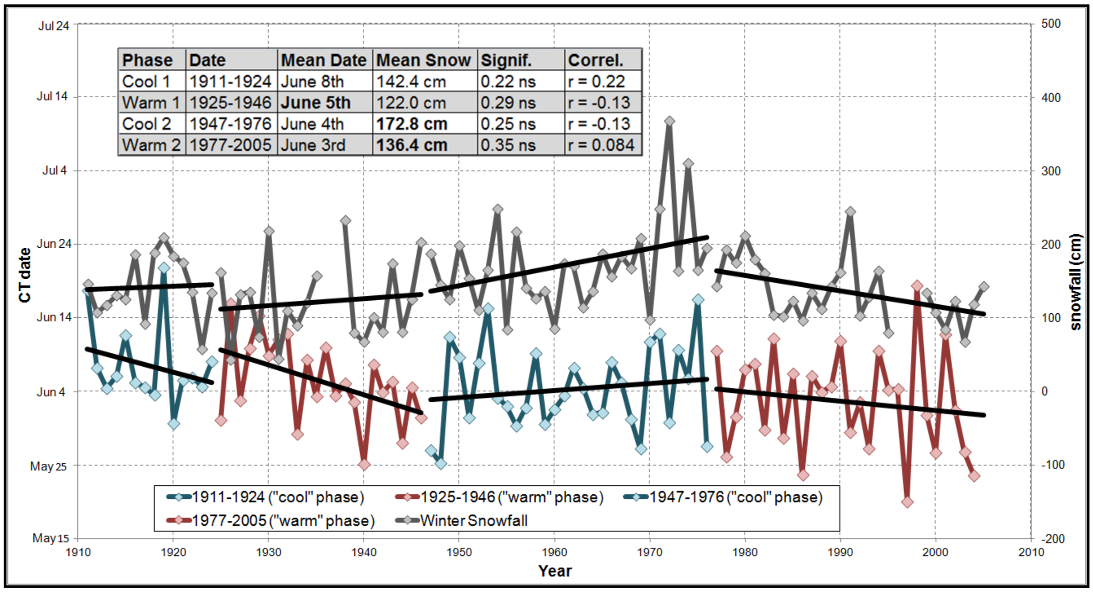
Phase	**Date**	**Mean Date**	**Mean Temp**	**Signif.**	**Correl.**
Cool 1	1911-1924	June 8th	-7.5 °C	0.11 ns	r = 0.36
Warm 1	1925-1946	**June 5th**	-6.1 °C	0.46 ns	r = -0.025
Cool 2	1947-1976	June 4th	-6.9 °C	0.30 ns	r = 0.11
Warm 2	1977-2005	June 3rd	-6.0 °C	**0.041 sig**	r = 0.33

Figure 4.12: CT dates for the Bow River and mean winter temperature at Banff for 1911-2005 broken into the PDO phases. Chart entries in bold indicate a significant relationship between the CT date and mean winter temperature for that phase. Black lines represent trends through each PDO phase for each variable. Correlation is between the annual values.

4.4 The Jasper climate record

4.4.1 Correlation between the Jasper and Banff climate records

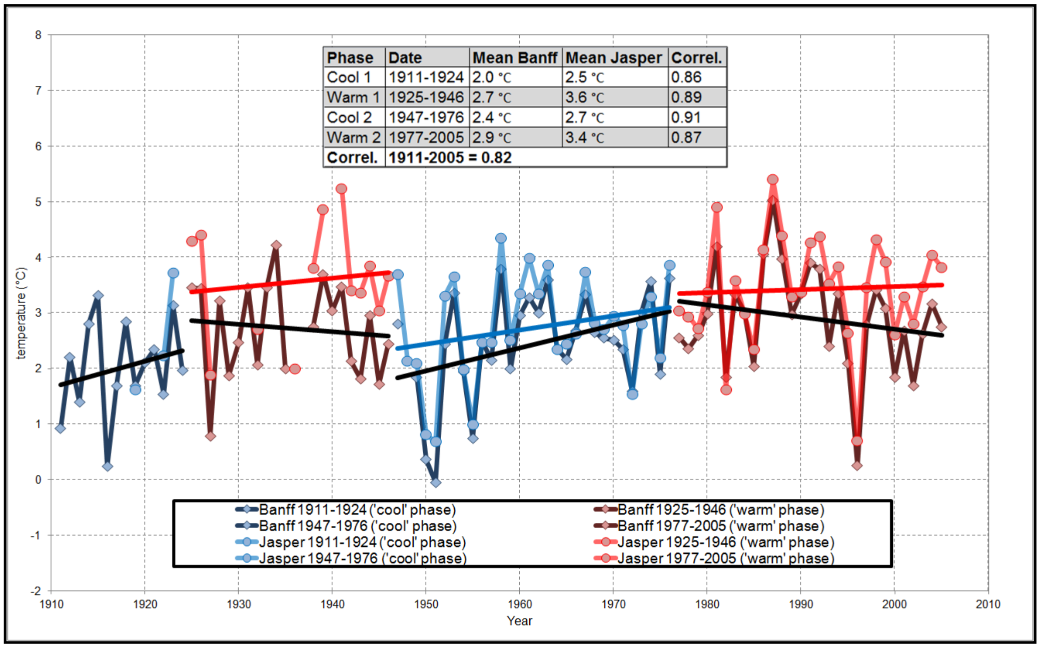
The Jasper climate record is not as strong as that for Banff as there are more missing data in the Environment Canada HCN Jasper record than at Banff. However, previous work



Phase	Date	Mean Date	Mean Snow	Signif.	Correl.
Cool 1	1911-1924	June 8th	142.4 cm	0.22 ns	r = 0.22
Warm 1	1925-1946	**June 5th**	122.0 cm	0.29 ns	r = -0.13
Cool 2	1947-1976	June 4th	**172.8 cm**	0.25 ns	r = -0.13
Warm 2	1977-2005	June 3rd	**136.4 cm**	0.35 ns	r = 0.084

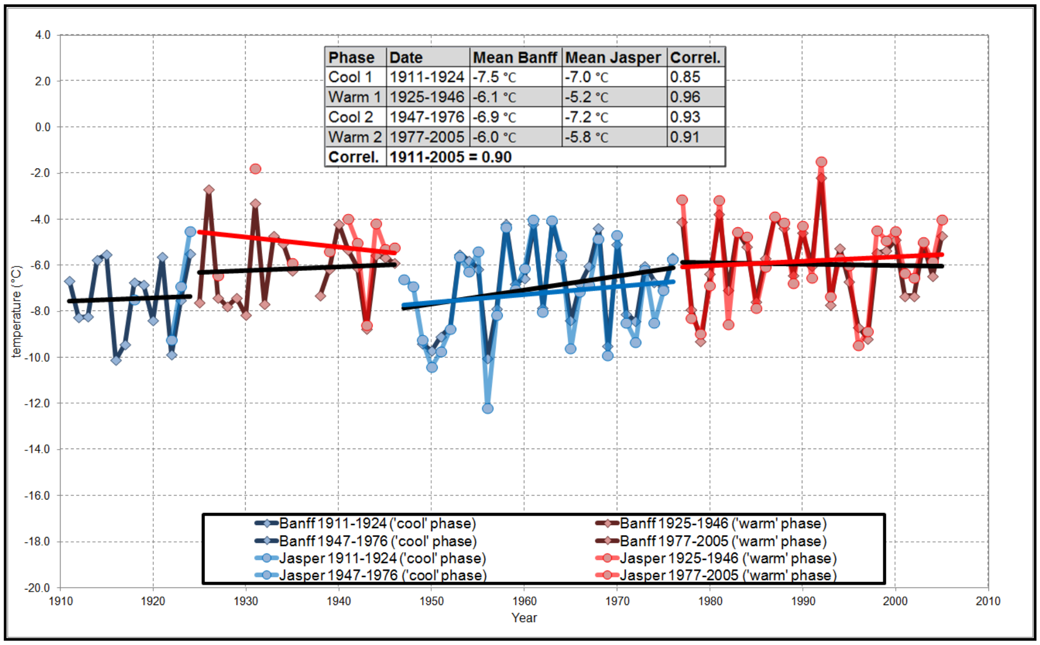
Figure 4.13: CT dates for the Bow River and winter snowfall at Banff for 1911-2005 broken into the PDO phases. None of these periods show a significant relationship between the CT date and winter snowfall. Black lines represent trends through each PDO phase for each variable. Correlation is between the annual values.

has indicated similarities in the patterns between these two records, especially evidence of decadal scale patterns (Luckman, 1998). While there are some differences between the two climate records, especially in relation to precipitation, the overall patterns appear similar (Luckman & Seed, 1995). Therefore the Jasper climate record can be compared to the record at Banff to see if similar long term and PDO related climate forcing are evident in both. The four parameters that were compared were mean annual temperature, mean winter temperature, annual precipitation, and winter snowfall (Figures 4.14-4.17) as these were the parameters identified as having the best relationships to streamflow data from the Banff analysis. The annual and winter (November - March) temperature records between Banff and Jasper are very well correlated (Figures 4.14 and 4.15, r = 0.82 annual, r = 0.90 winter, 1911-2005) with similar trends and differences in means between the “cool” and “warm” phases of the PDO. The average temperatures at Jasper are slightly higher than at Banff because Jasper is about 350m lower in elevation. Missing data from the Jasper record between 1911 and 1946 weakens the analyses for the two earlier phases of the PDO especially for the precipitation data. As noted by Luckman, 1998 and Watson *et al*, 2008, the relationships between the precipitation records for Jasper and Banff are much more variable than for the temperature data. There are significant relationships (at the 99% confidence interval) between both annual precipitation and winter snowfall between the two sites but very low correlation (Figures 4.16, 4.17; r=0.12 and r= 0.48, respectively) which reflects different trends in the basins reflecting the high regional variability of precipitation in the Canadian Rockies. The high correlations for the 1911-1924 "cool" phase are only based on one or two data points. Nevertheless the snowfall data demonstrates some similarities between phases. A strong connection has generally been established between the PDO and snowfall conditions (Mote, 2006) and this is seen in the differences in means between the "cool" and "warm" phases. There is higher total snowfall during the "cool" phases at both sites. Despite the differences in the precipitation patterns at the two sites, the strong precipitation relationships and correlation in temperatures between the two sites suggests that climate trends are similar between the two areas. Although there are differences in snowfall



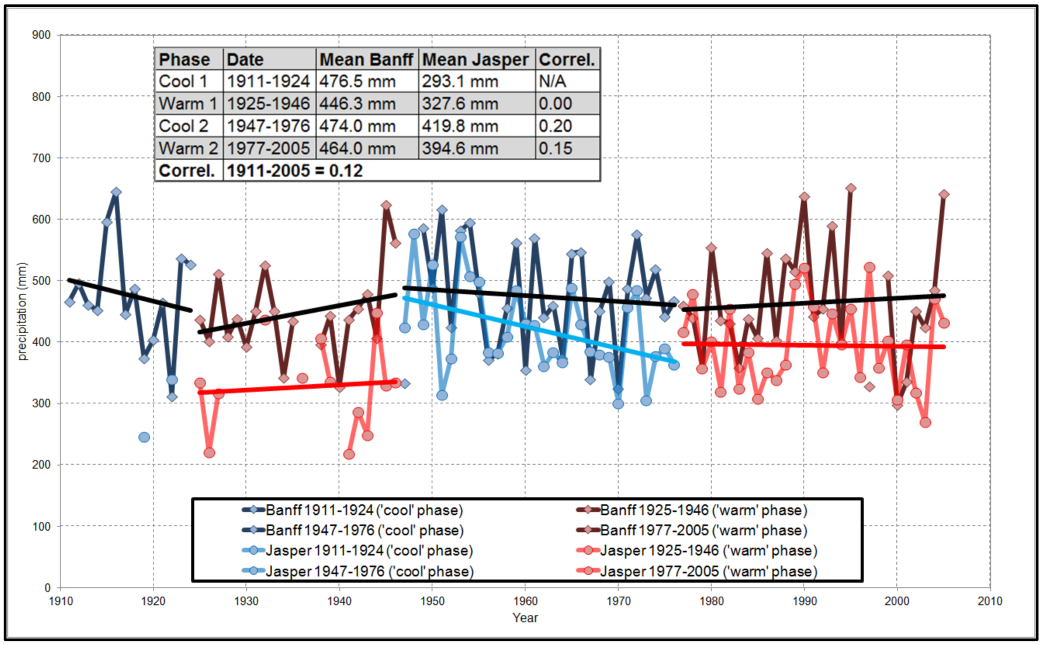
Phase	Date	Mean Banff	Mean Jasper	Correl.
Cool 1	1911-1924	2.0 °C	2.5 °C	0.86
Warm 1	1925-1946	2.7 °C	3.6 °C	0.89
Cool 2	1947-1976	2.4 °C	2.7 °C	0.91
Warm 2	1977-2005	2.9 °C	3.4 °C	0.87
Correl.	**1911-2005 = 0.82**			

Figure 4.14: Banff and Jasper mean annual temperatures compared over the PDO phases. Trendlines for Banff are shown in black and trendlines for Jasper are shown in red and blue. Correlation is between the annual values.



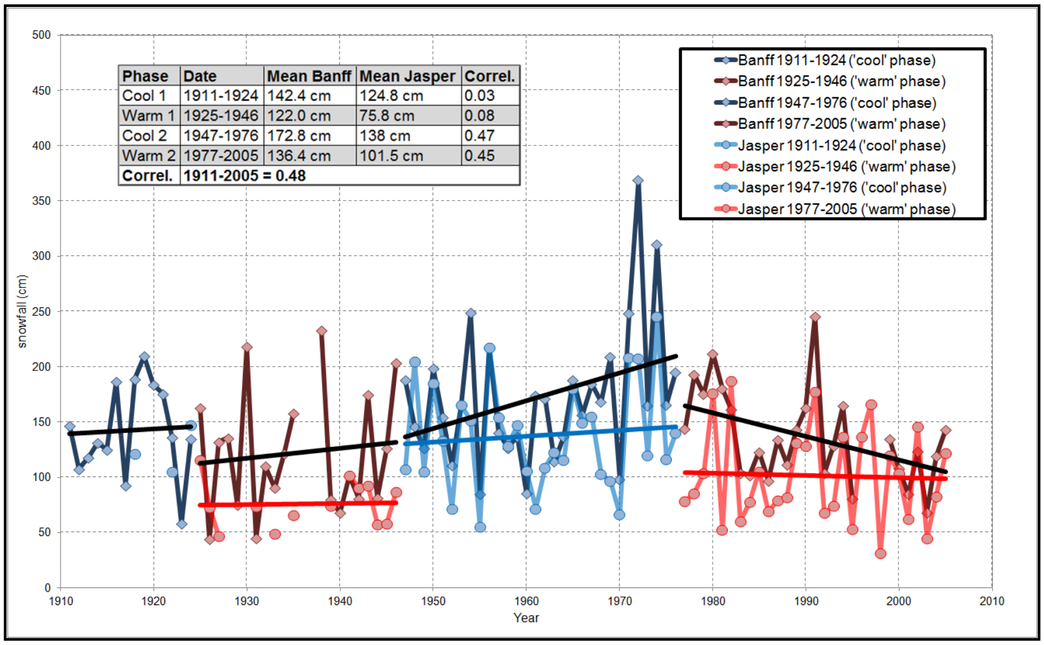
Phase	Date	Mean Banff	Mean Jasper	Correl.
Cool 1	1911-1924	-7.5 °C	-7.0 °C	0.85
Warm 1	1925-1946	-6.1 °C	-5.2 °C	0.96
Cool 2	1947-1976	-6.9 °C	-7.2 °C	0.93
Warm 2	1977-2005	-6.0 °C	-5.8 °C	0.91
Correl.	1911-2005 = 0.90			

Figure 4.15: Banff and Jasper mean winter temperatures compared over the PDO phases. Trendlines for Banff are shown in black and trendlines for Jasper are shown in red and blue. Correlation is between the annual values.



Phase	Date	Mean Banff	Mean Jasper	Correl.
Cool 1	1911-1924	476.5 mm	293.1 mm	N/A
Warm 1	1925-1946	446.3 mm	327.6 mm	0.00
Cool 2	1947-1976	474.0 mm	419.8 mm	0.20
Warm 2	1977-2005	464.0 mm	394.6 mm	0.15
Correl.	1911-2005 = 0.12			

Figure 4.16: Banff and Jasper annual precipitation compared over the PDO phases. Trendlines for Banff are shown in black and trendlines for Jasper are shown in red and blue. Correlation is between the annual values.



Phase	Date	Mean Banff	Mean Jasper	Correl.
Cool 1	1911-1924	142.4 cm	124.8 cm	0.03
Warm 1	1925-1946	122.0 cm	75.8 cm	0.08
Cool 2	1947-1976	172.8 cm	138 cm	0.47
Warm 2	1977-2005	136.4 cm	101.5 cm	0.45
Correl.	**1911-2005 = 0.48**			

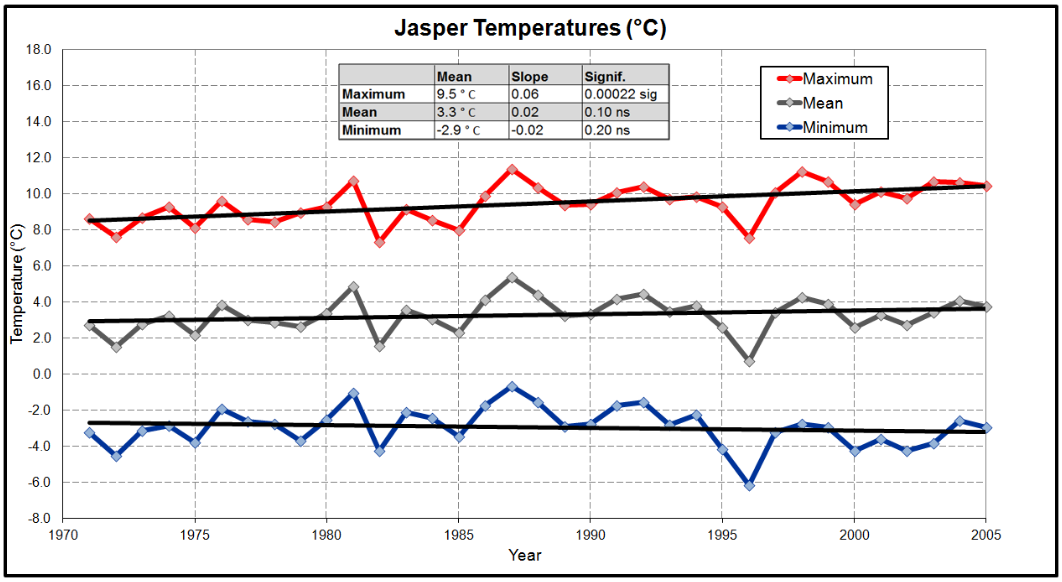
Figure 4.17: Banff and Jasper winter snowfall compared over the PDO phases. Trendlines for Banff are shown in black and trendlines for Jasper are shown in red and blue. Correlation is between the annual values.

amounts with Jasper averaging only ca. 65% of the Banff total during the last complete PDO cycle, there is a similar pattern of fluctuations over the common record.

The difficulty comparing the Athabasca hydrological trends with the climate record results from the short recent streamflow record and the poor climate record (4-5 years) for the earlier 1914-1931 period with hydrological data. However there are possibilities to infer relationships based on similarities to the relationships noted between the PDO, temperatures and precipitation in the Banff record. Generally 20th century changes in the Athabasca record can be inferred by comparison with the Bow record for those periods without data directly from Jasper. Although there are differences in the observed magnitude of annual temperature (mean range 0.3°C – 0.9°C) and precipitation changes (range 54.2 mm – 69.4 mm in later half of the century) between the two locations but the pattern of variability may be similar. The variability within the winter climate data is smaller than that of the annual data and so may be more strongly similar.

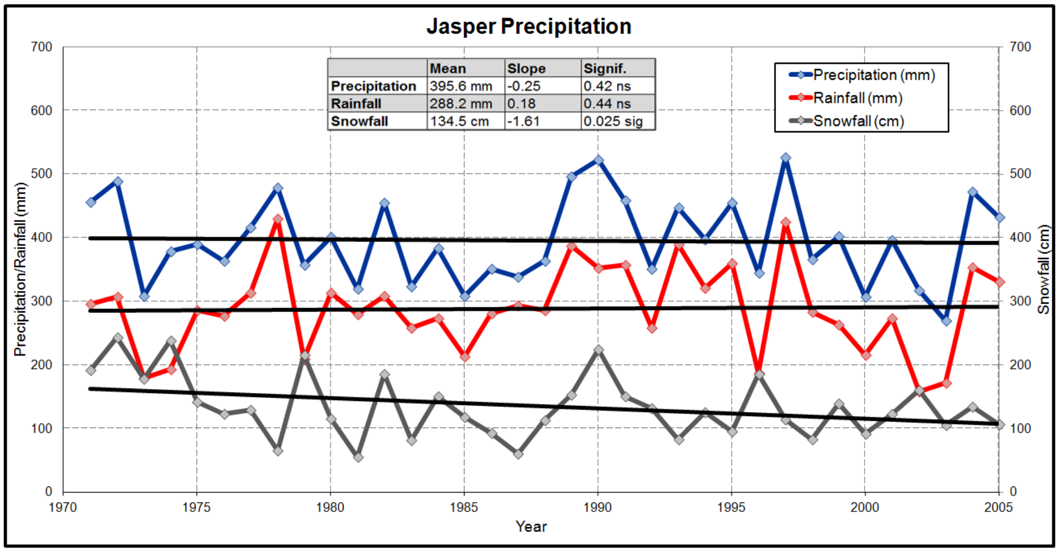
4.4.2 The Jasper climate record and the Athabasca River hydrological record

A comparison between climate data and streamflow data on the Athabasca River was only conducted for the 1971-2005 period with 100% overlap between the hydrological and climate data. The 1914-1931 period has only sporadic climate and hydrological records and the overlap is poor. The Jasper temperature trends shown in Figure 4.18 demonstrate increases in maximum (significant) and mean temperatures with a minor decrease in minimum temperatures over the record. Mean temperatures between Jasper and Banff match up quite well (Figures 4.14 and 4.15). The precipitation trends differ over the 1971-2005 period (Figures 4.16 and 4.17) with the Jasper site showing a minor increase in rainfall, a minor decrease in overall precipitation but a major significant decrease in snowfall between 1971 and 2005 (Figure 4.19). This decrease in snowfall is consistent with observations from other studies but it is not matched with an increase in the amount of annual rainfall which has been regularly noted (Figure 4.19, Mote *et al*, 2005). Figure 4.20 shows a significant increase in winter (November – March) mean temperatures at Jasper corresponding with a significant decrease in winter (November – March) snowfall suggesting a shorter period of cold temperatures that promote snowfall



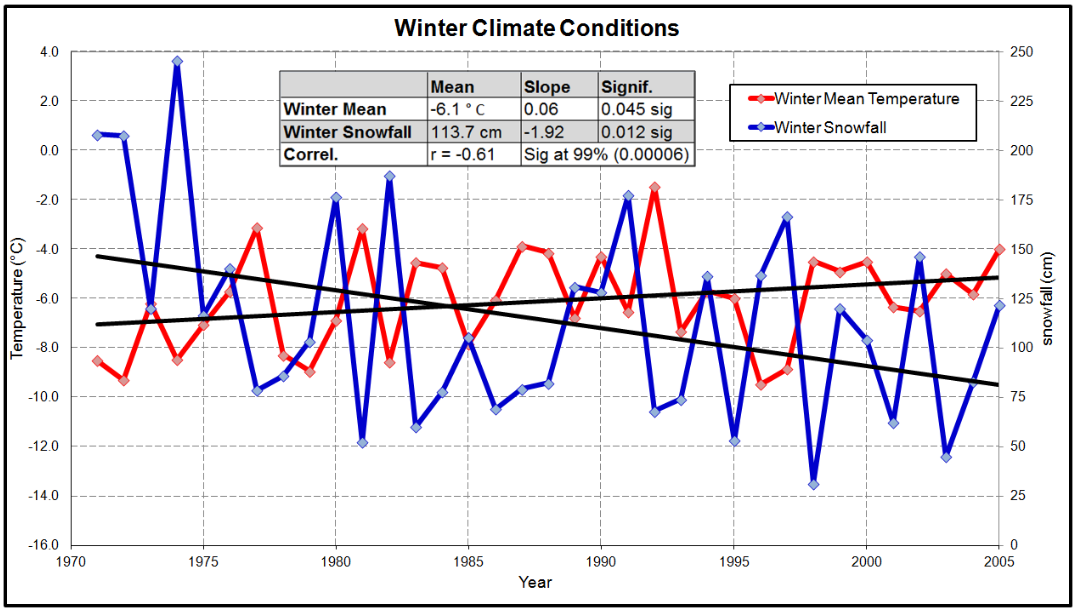
	Mean	Slope	Signif.
Maximum	9.5 ° C	0.06	0.00022 sig
Mean	3.3 ° C	0.02	0.10 ns
Minimum	-2.9 ° C	-0.02	0.20 ns

Figure 4.18: Mean, maximum, and minimum annual temperatures for Jasper 1971-2005.



	Mean	Slope	Signif.
Precipitation	395.6 mm	-0.25	0.42 ns
Rainfall	288.2 mm	0.18	0.44 ns
Snowfall	134.5 cm	-1.61	0.025 sig

Figure 4.19: Annual rainfall, snowfall, and combined precipitation levels for Jasper 1971-2005.



	Mean	Slope	Signif.
Winter Mean	-6.1 ° C	0.06	0.045 sig
Winter Snowfall	113.7 cm	-1.92	0.012 sig
Correl.	r = -0.61	Sig at 99% (0.00006)	

Figure 4.20: Winter (November – March) mean temperatures and winter (November – March) snowfall accumulation for Jasper 1971-2005. Correlation is between the annual values.

than was previously the case. This could be a major influence on streamflow as without a build-up of winter snow the melt peak will be much smaller causing less water availability downstream.

When examining the Athabasca hydrological trends it is important to remember that none of the four hydrological measures were found to have significant trends over the study period. Possibly, if a longer time interval of data was available, some of these trends would have been seen to be significant. The annual measures of hydrologic variability were expected to show relationships with the annual and winter climate data so only mean annual flow and CT date have been examined here for hydroclimate linkages. As with the Bow record, the Athabasca shows a decrease in mean annual flows that corresponds with an increase in mean winter temperatures (r=-0.2 ns, Figure 4.21) and a significant decrease in winter snowfall (r=0.47, p=0.002, Figure 4.22). CT dates show a positive relationship with winter temperatures (CT coming earlier, Figure 4.23) and a negative relationship with winter snowfall (Figure 4.24) but only the winter snowfall relationship approaches statistical significance (r=-0.27, p=0.94). This is similar to observations in the Bow system, as winter temperatures increase there is the potential for

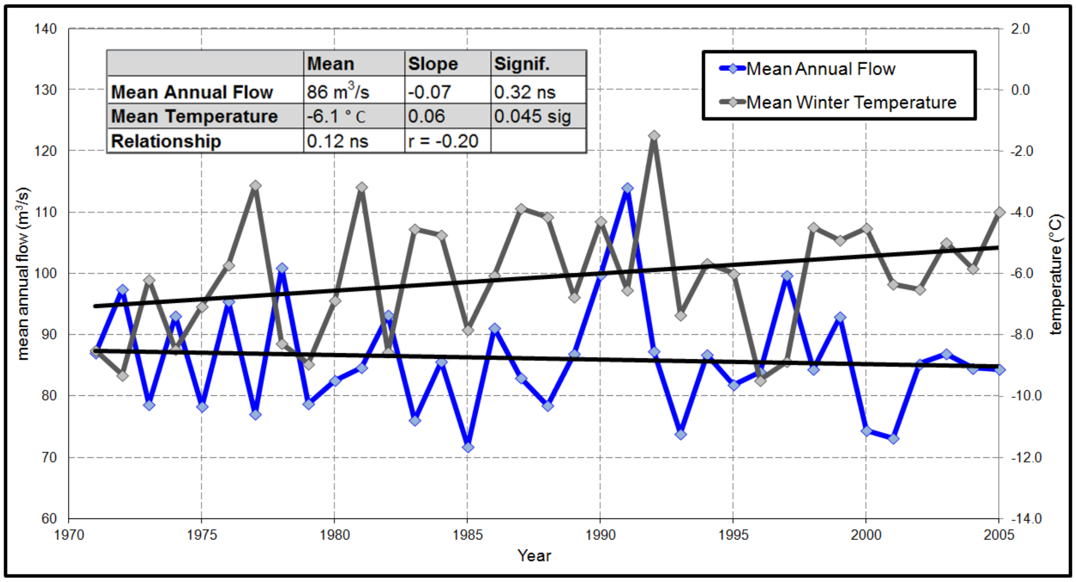
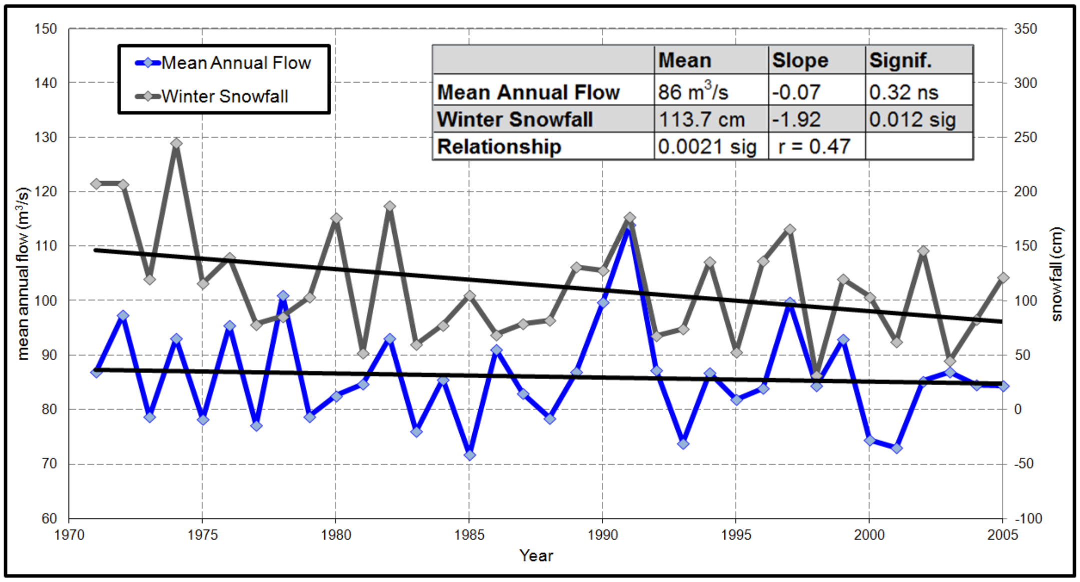
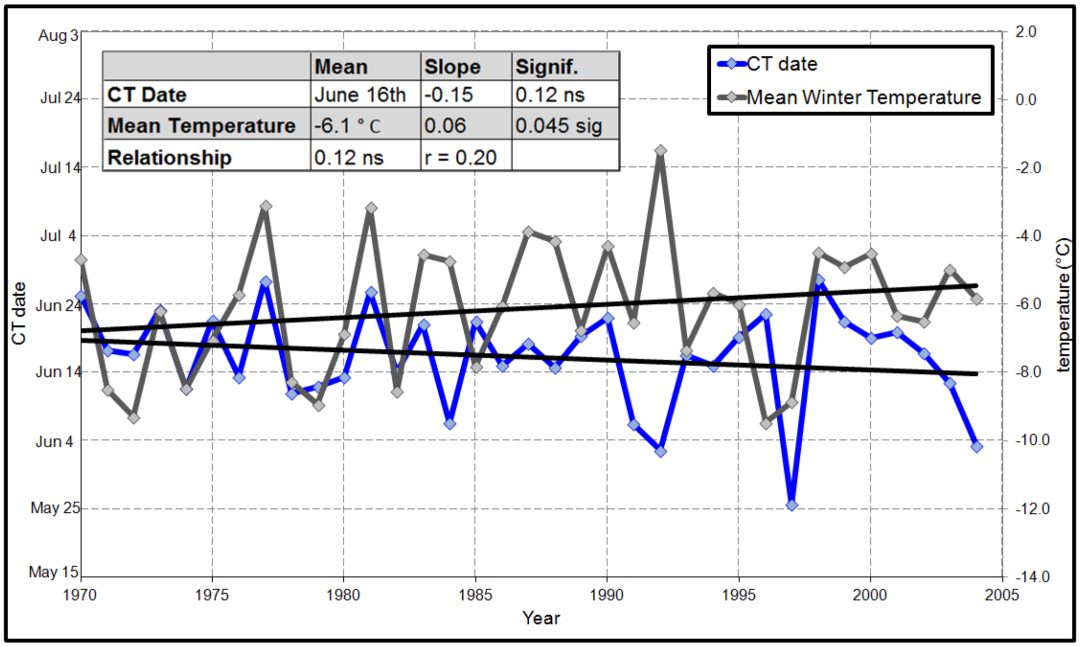


Figure 4.21: Athabasca River near Jasper mean annual flow and Jasper mean winter temperature for the period of 1971-2005. Correlation is between the annual values.



	Mean	Slope	Signif.
Mean Annual Flow	86 m^3/s	-0.07	0.32 ns
Winter Snowfall	113.7 cm	-1.92	0.012 sig
Relationship	0.0021 sig	r = 0.47	

Figure 4.22: Athabasca River near Jasper mean annual flow and Jasper winter snowfall for the period of 1971-2005. Correlation is between these two values.



	Mean	Slope	Signif.
CT Date	June 16th	-0.15	0.12 ns
Mean Temperature	-6.1 °C	0.06	0.045 sig
Relationship	0.12 ns	r = 0.20	

Figure 4.23: Athabasca River near Jasper CT date and Jasper mean winter temperature for the period of 1970-2004. Correlation is between these two values.

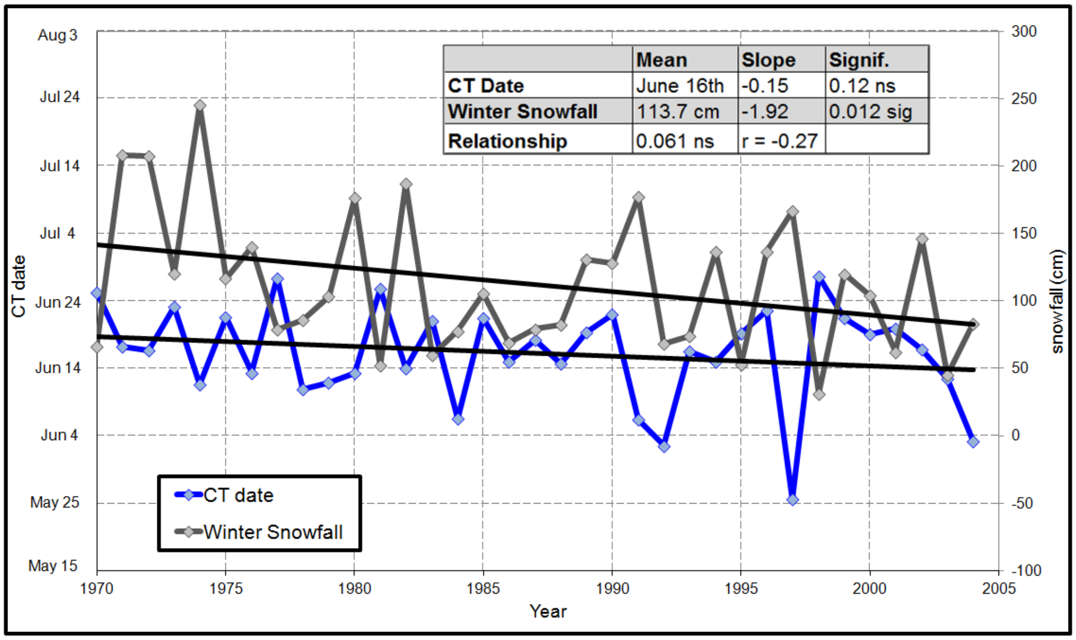
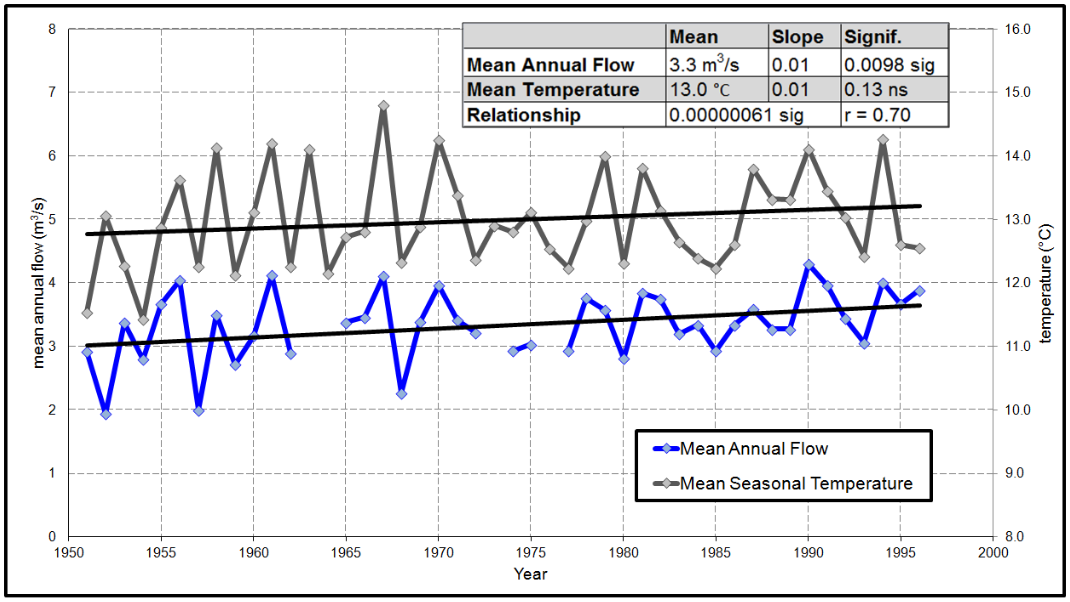


Figure 4.24: Athabasca River near Jasper CT date and Jasper winter snowfall for the period of 1970-2004. Correlation is between these two values.

greater melt, smaller snowpacks and lower accumulation on the glaciers. These similarities between the two sites suggest similar climate forcing is driving streamflow and therefore the potential to use the Bow record to predict trends in the missing Athabasca data can again be suggested.

4.4.3 The Jasper climate record and the Sunwapta River hydrological record.

The closest climate stations to the Sunwapta River gauge at Athabasca Glacier are Jasper and Lake Louise. Since Jasper is within the same watershed and is closer, this climate record was selected for comparison with the Sunwapta record. As Sunwapta hydrological data only exist for the June 1 – September 30 period, the climate parameters were analyzed for this seasonal period in addition to the annual and winter periods. The most important result from these analyses is the highly significant relationship between mean June-September flow and mean June-September temperatures (r=0.7, p>0.999, Figure 4.25), no relationships were observed with mean annual flow and any of the precipitation measures (annual precipitation, June – September precipitation, or

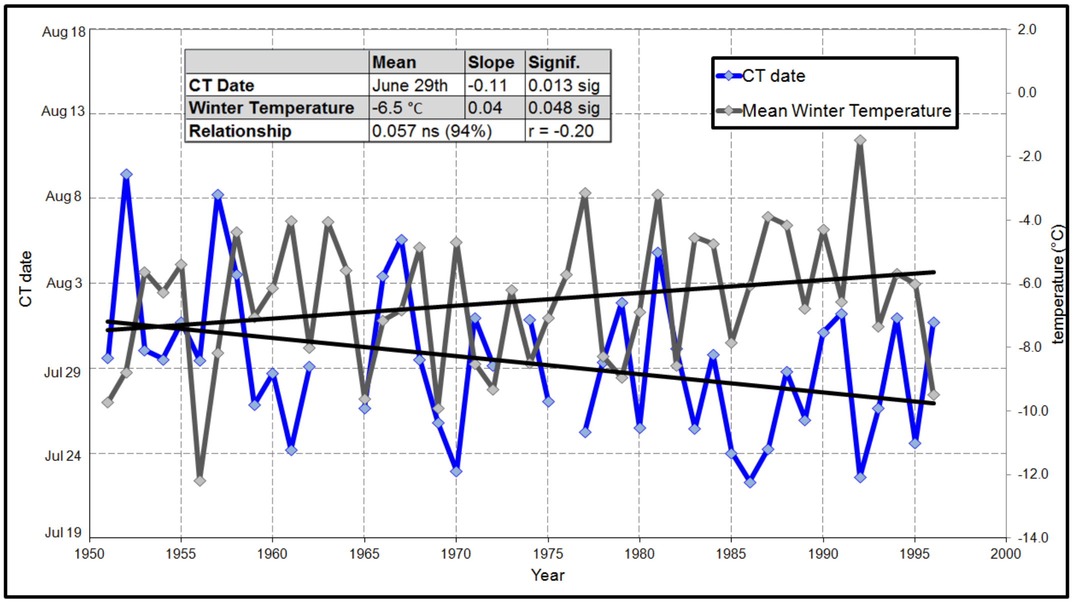


	Mean	Slope	Signif.
Mean Annual Flow	3.3 m^3/s	0.01	0.0098 sig
Mean Temperature	13.0 °C	0.01	0.13 ns
Relationship	0.00000061 sig		r = 0.70

Figure 4.25: Sunwapta River at Athabasca Glacier seasonal (June – September) mean annual flow and Jasper seasonal (June – September) mean temperatures for the period of 1951-1996. Correlation is between the annual values.

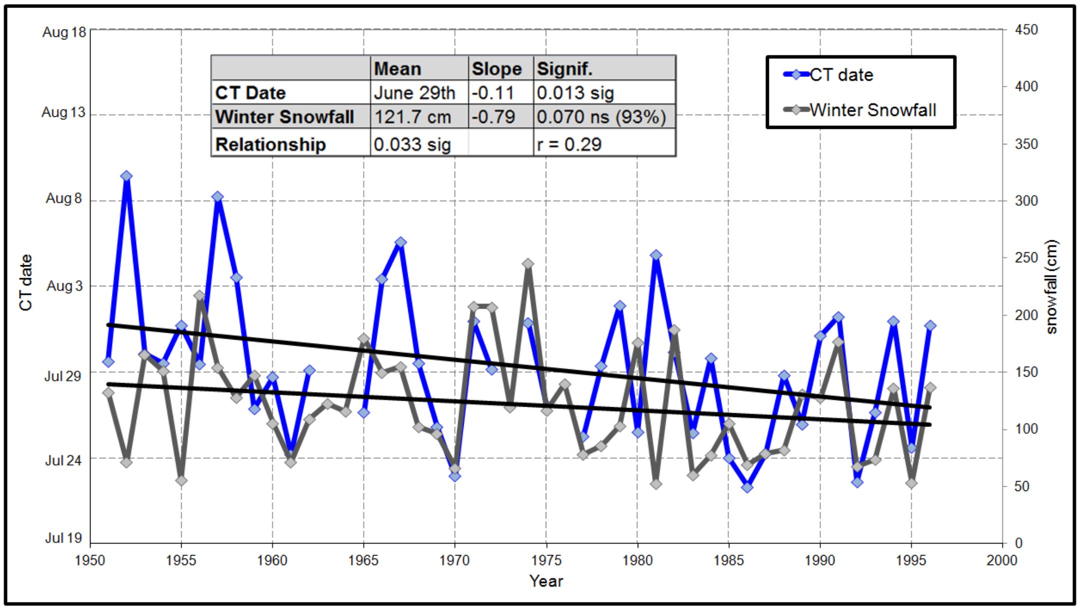
November – March precipitation). As might be anticipated, daily discharge at Sunwapta are primarily dependent on temperature-driven, contemporaneous snow and ice melt from Athabasca Glacier with much less direct input from precipitation. Analysis of the CT date showed a negative relationship with winter temperatures (r= -0.20, p=0.94, Figure 4.26) and a positive relationship with winter snowfall (r=0.29, p=0.97, Figure 4.27) i.e. greater snowfalls result in a later CT (although both show significant decreasing trends over the period of record). There were no significant relationships between CT and annual or summer temperatures. These trends show that the winter climate conditions have a strong effect on the timing of discharge in the study basins but less influence on streamflow magnitudes. The CT trend (as observed in Chapter 3) is even greater in the Sunwapta basin because of its greater sensitivity to snow and ice melt sources of streamflow.

The results on the Sunwapta River suggest that on a year to year basis the temperature effect is the most important parameter that is causing variation in this proglacial basin. The proximity to the glacier and the fact that most of the inputs come from this source



	Mean	Slope	Signif.
CT Date	June 29th	-0.11	0.013 sig
Winter Temperature	-6.5 °C	0.04	0.048 sig
Relationship	0.057 ns (94%)		r = -0.20

Figure 4.26: Sunwapta River at Athabasca Glacier seasonal (June – September) CT date and Jasper winter mean temperature for the period of 1951-1996. Correlation is between these seasonal values.



	Mean	Slope	Signif.
CT Date	June 29th	-0.11	0.013 sig
Winter Snowfall	121.7 cm	-0.79	0.070 ns (93%)
Relationship	0.033 sig		r = 0.29

Figure 4.27: Sunwapta River at Athabasca Glacier seasonal (June – September) CT date and Jasper winter snowfall for the period of 1951-1996. Correlation is between these seasonal values.

controls the importance of summer temperatures which are seen to be even more critical than winter precipitation values. This is not observed in the larger basins where winter conditions (especially precipitation) are more important for identifying sources of variation. This suggests that since glacial melt-derived discharge is only a relatively small component of discharge in the larger basins the summer temperature effect is not seen in those records. The strong link between summer temperatures and discharge of the Sunwapta River highlights a major difference between highly glacierized basins and those with less glacial derived input.

Analysis of the Sunwapta record based on PDO phases did not reveal statistical linkages with the CT data. The mean annual (summer) flow volume was significantly correlated with the seasonal temperatures in both phases but at a much lower level than for the entire period of record and did not demonstrate any differences in mean values or trends between the two PDO phases (data not shown) .

4.5 Conclusions

This analysis of the climate record at Banff, and to a lesser extent Jasper, indicate that the most important climate linkages are related to the phase shifts of the PDO. Significant changes in snowfall and to a lesser extent winter temperatures are observed throughout the region in relation to these phase shifts. These variations drive the main hydrological trends in the study basins, especially on the Bow River. Additionally some long term trends are observed particularly with regard to increasing temperatures (mean and minimum) and winter snowfall that are influencing the trend to lower mean annual flow and earlier CT timing in the Bow basin. These results are related to changes either within a PDO phase or longer term changes. Few major long term trends are observed in the Bow record as they are modulated by the multidecadal variability in the records. The presence of decadal scale variability in the climate parameters explains why the Bow streamflow record demonstrates strong significant links to the PDO but not to long term changes. This suggests that the Pacific Decadal Oscillation is a major influence on the hydroclimate in the Canadian Cordillera. Currently the PDO is only recognized by a small group of scientists and this research suggests that its role needs to be more widely acknowledged in the hydrological community.

Comparison of the shorter Athabasca hydrological record with Jasper climate data showed similar trends to those observed on the Bow and Banff. Both the mean annual flow data and the CT timing relate significantly to winter snowfall and are influenced (but not significantly) by winter temperatures. This does show a minor difference between the two sites as the Bow CT date did not correlate well to winter snowfall at Banff over the entire record, however, there was a non-significant correlation seen in the 1977-2005 'warm' PDO phase. Generally however the trends at the two sites are quite similar. Comparative analysis of the Banff and Jasper climate data shows influence of the PDO in temperature and precipitation parameters at both sites. However, although the temperatures are well correlated the precipitation records are less so.

Comparison of the seasonal Sunwapta discharge record with Jasper summer temperatures shows a strong, significant relationship over the 1951-1995 period. However, and surprisingly, the correlation with Jasper winter precipitation values was not significant, possibly because Jasper precipitation is not an ideal measure of precipitation at Athabasca Glacier. The winter snowfall did correlate significantly with the earlier timing of CT date which was also closely related (at the 94% confidence level) to the winter temperature conditions. This demonstrates different glacier-related streamflow controls at the proglacial Sunwapta basin than are found on the much larger Bow and Athabasca basins. All three of these rivers have demonstrated that there is a strong link between the variations in streamflow and climate in the southern Canadian Cordillera.

Chapter 5

5 A simple visual technique for identification of regime change using daily streamflow data from the Bow and Athabasca Rivers

5.1 Introduction: Alternative strategies for detection and communication of stream regime change

Chapter three analyzed the streamflow data in the Upper Athabasca and Upper Bow watersheds using traditional statistical methods. However, it is known that different people process information differently with some leaning towards technical and empirical analysis methods and others preferring observation and modeling representations (Phal-Wostl, 2007). Phal-Wostl (2002) describes how the typical engineering approach to water policy has moved into a community- based approach where public opinion is strongly accentuated. Therefore, to assemble a comprehensive set of data for decision makers it may be best to use several approaches aligning the data to differing knowledge levels (Phal-Wostl, 2007, Gordon *et al*, 2010). By creating a visual technique of analysis along with the traditional statistical methodology, non-technical individuals with input to the planning process may gain an improved understanding of the data helping to make more informed decisions. In addition, traditional statistical streamflow analysis is based on parametric statistics and the hypotheses that accompany such analyses. Yet non-parametric analysis has been found to be a good choice to use in streamflow analysis with data sets of insufficient size to provide a normal distribution (Rood *et al*, 2005). Unpublished work by Dr Chris Smart on the Medway Creek in London, Ontario has shown that visualization techniques utilizing a roving window to screen the data can provide representations of daily discharge, determine mean discharge plus estimates of daily extremes and annual patterns. In this chapter an attempt is made to use these approaches to create a visually-appealing technique that provides a graphic display of temporal streamflow variation that can be used to examine variations in the hydrological regime over time.

5.2 Methodology: Development of the visualization technique

The HYDAT daily data for the Bow River at Banff and Athabasca River near Jasper used in the statistical study were also used to develop this technique. In performing comparative visual analysis it was determined that using runoff values (discharge per unit area) for the catchment would be superior to using discharge data as standardized runoff data are more easily compared across basins of varying size. Runoff is also a term that is used in even the most basic hydrological texts (Christopherson & Bryne, 2009) and so those with less technical backgrounds may recognize it. Therefore the daily discharge data (m^3/s) were converted to mm/day/ km^2 for the Bow River at Banff (2210km^2) and Athabasca River near Jasper (3870km^2).

In creating a visual technique it is necessary to aggregate the data to emphasize patterns of interest and reduce background "noise". The desired pattern from this study should emphasize temporal patterns in the data sets at decadal or longer scales rather than at interannual scales. Using daily data alone would produce a pattern of individual extreme events, indicate few trends and defeat the goals of this study. Figure 5.1 plots daily discharge data for each year of the Banff record using a single scale of equal divisions up to the maximum daily discharge ever recorded. These extreme discharge events extend the scale and the upper intervals of discharge are rarely used, resulting in very broad, degraded patterns of streamflow. Aggregating the data over (i) several days removes individual extremes and (ii) including the data for the same day over several years can bring out the desired longer term trends. These goals were achieved empirically by deriving data from an ensemble of values around each data point and subsequently smoothing the data with a Hanning filter[7]. Filtering these data using a roving "boxing" pattern reduces the influence of extreme or anomalous values. For individual dates the "box" is used to create a distribution of N values that consist of the daily values for n^1

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[7] A Hanning filter is designed to reduce the edge effect of anomalous values and increase the signal-to-noise ratio (Dietrich *et al*, 2007).

days before and after the selected day for each of n^2 years prior and subsequent to the year in question.

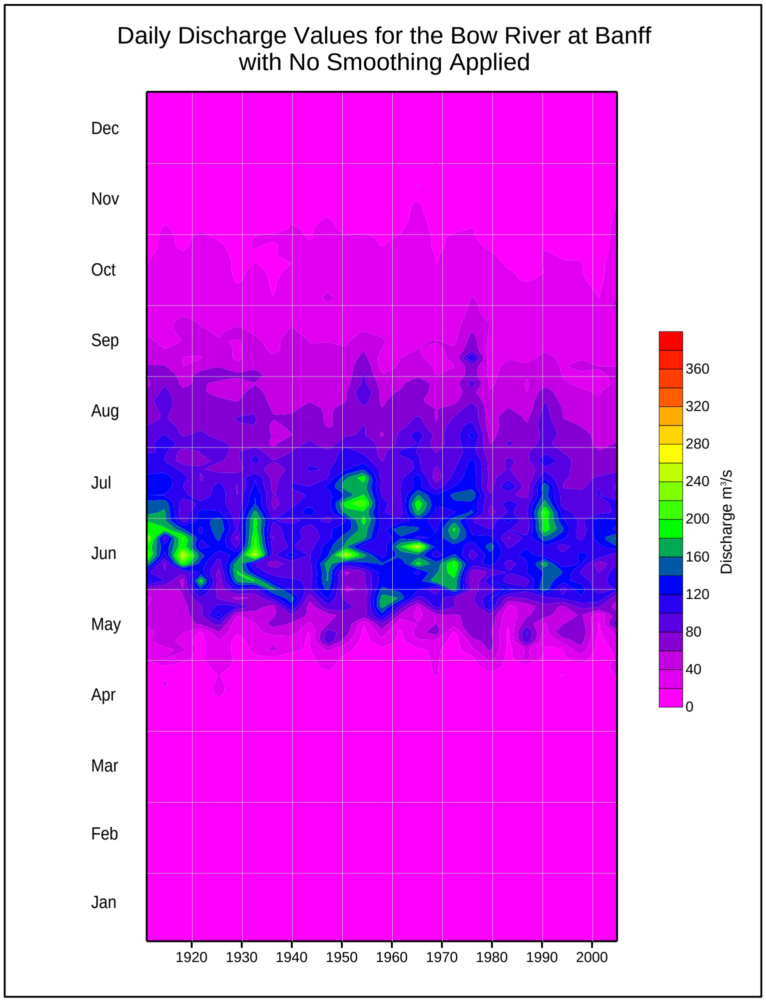

Figure 5.1: The daily discharge values (m^3/s) for the Bow River at Banff plotted with no smoothing applied and a single scale. Note the extreme events are difficult to view but there are points with values reaching the red portion of the scale.

The value given to each date is selected from the distribution of values within the “box” to represent the selected streamflow parameter for the discharge on that day. This allows the development of a representative picture of the overall trends and patterns within the data rather than focusing on the values by simply looking at the discharge numbers. The Bow River data were used in trials to determine the appropriate level of smoothing to create a runoff data set where extreme daily events did not dominate the overall picture.

Smoothing was run using all day-year combinations of 7, 15, and 31 (n^1) days and 5, 11, and 15 (n^2) years. Selection of the most useful day-year combination for the roving window results in the reduction of the available length of record, e.g. when n^2= 11 years, 5 years are lost from each end of the data set. Also, if the data are too smoothed, too much of the event signal is lost. Based on these factors it was determined that the most useful window size was a 15 day by 11 year window (N= 165 days). This enabled the development of an overall picture of the streamflow pattern without extreme daily events being emphasized and the loss of five years of data at the ends of the selected data sets was acceptable given the length of the Bow record. This 15 by 11 window was applied to the runoff datasets of both the Bow and Athabasca Rivers. Using a 15 day smoothing window also required the use of discharge data from the last 14 days of 1910 (Bow) and 1970 (Athabasca) plus discharge values from the first 14 days of 2006. One added advantage to the five year reduction to the Athabasca record is the removal of the effects of discharge from the pre-1976 PDO shift period. After the application of the “boxing” technique the data were run through the Hanning filter. By doing this the value of each day in the data set represented the daily portion of the window (for this study 15 days) combined based on a 15 day Hanning application so that greater weight was given to the actual day with weight decreasing as you move from the centre to the boundaries of the daily portion of the window. This allows for extreme events to be accounted for but not to dominate the visual representation as was seen in the original discharge data representation (Figure 5.1).

This technique presents a distribution of streamflow for a given date and year that permits an analysis of several components of that distribution. Several trials were run to determine diagnostic values to use to characterize median, minimum, and maximum runoff. A dynamic spreadsheet that had a 15 day by 11 year window screened with a Hanning filter application was set up to run this analysis and several percentile levels were tested using the Bow dataset to determine the most appropriate percentiles to represent the different levels of runoff. The median percentile was set at 50% but selection of measures for minimum and maximum runoff needed to avoid outliers and select more representative values for these patterns. Trials for the 1st, 5th, and 10th percentiles were run for minimum value analysis and 99th, 95th, an 90th for maximum value analysis (Figures 5.2 and 5.3). The 1st, 5th, and 10th percentile values for the Bow (Figure 5.2) show similar patterns of lower and higher streamflow. However, as the 1st percentile is based on a small sample of streamflow (at a level surpassed on all but 1-2 days annually) these values are considered too extreme and the visual appearance is quite "blocky" and does not show clear patterns. While some of this "blocky" pattern can be attributed to the use of one scale for all three plots the low range of values for the 1st and 5th percentile also add to the discontinuities between levels. The 5th and 10th percentiles give more interpretable patterns with the 10th percentile showing consistent periods that provide the most robust sample of low streamflow characteristics. Therefore the 10th percentile values were selected to represent low runoff as the colour grades merge

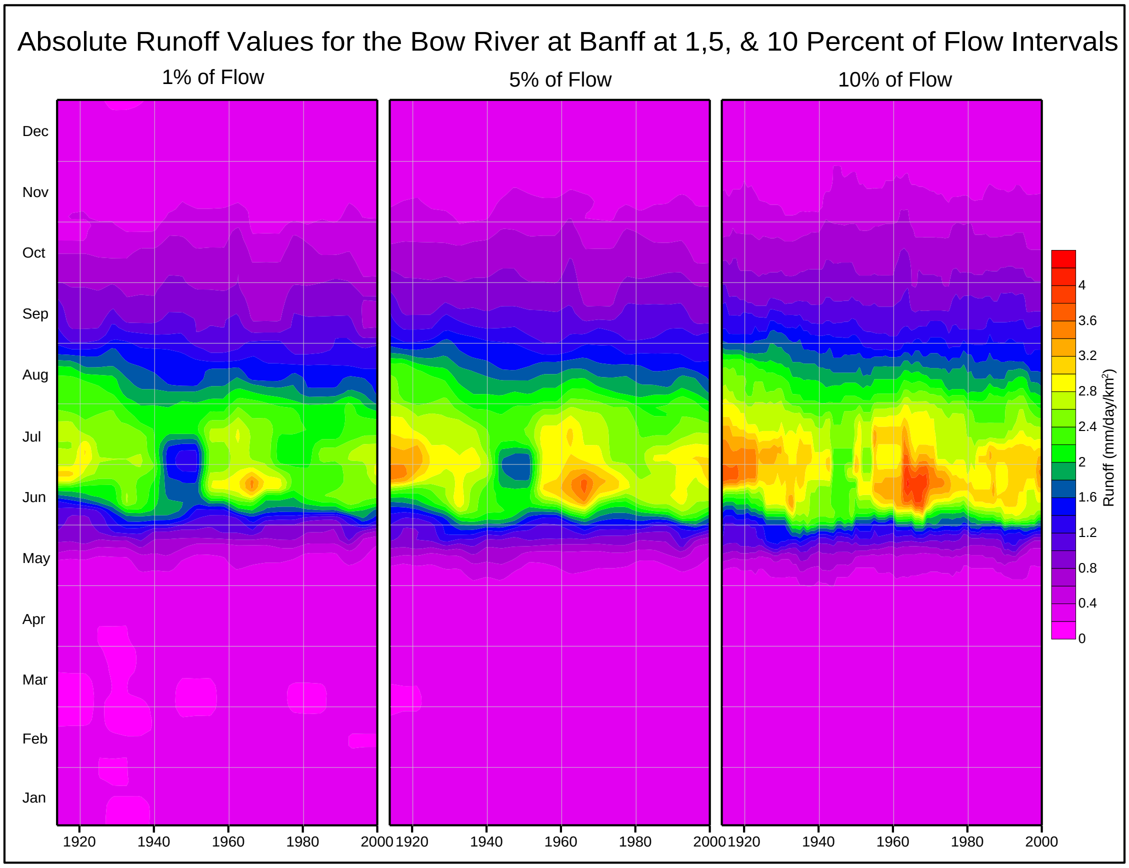

Figure 5.2: The absolute runoff values for the Bow River at Banff for the 1st, 5th, and 10th percentiles displayed using a common scale. The 10th percentile demonstrates a more robust profile that places the range of values in a gradual perspective.

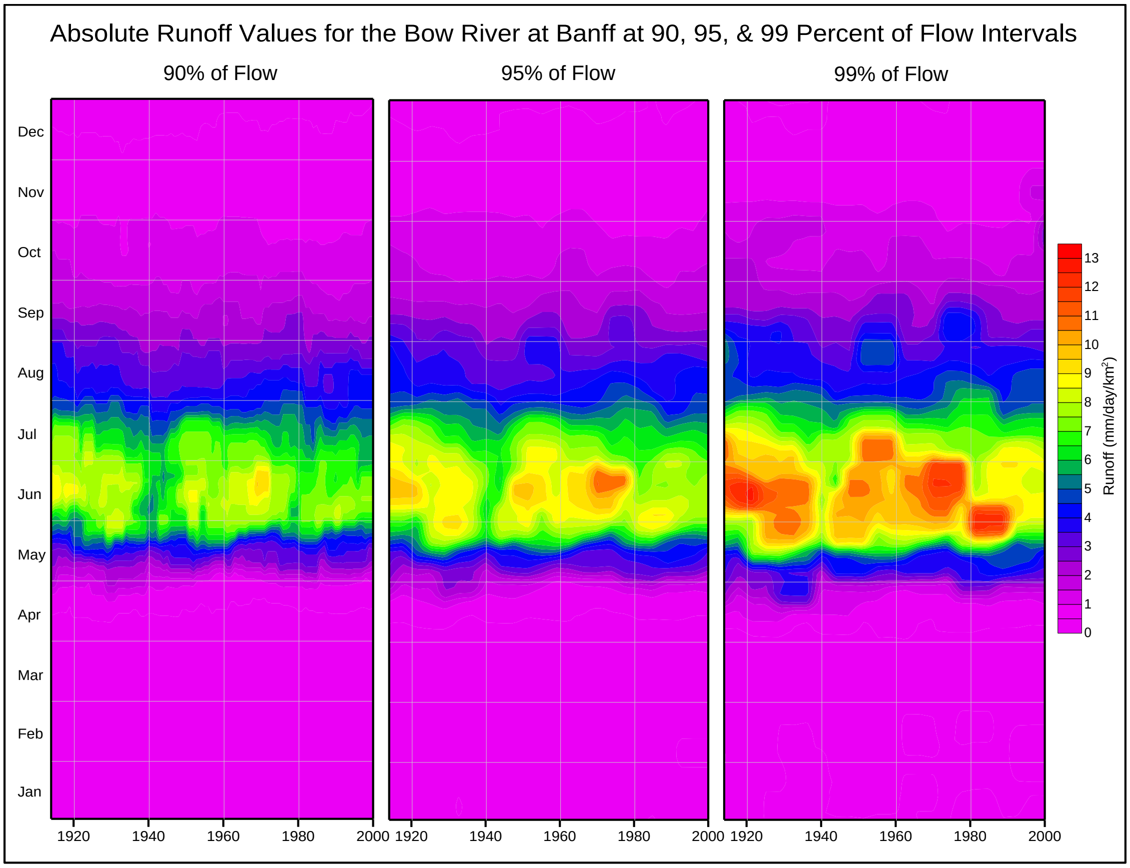

Figure 5.3: The absolute runoff values for the Bow River at Banff for the 90th, 95th, and 99th percentiles displayed using a common scale. The 90th percentile demonstrates a more robust profile that places the range of values in a gradual perspective.

gradually into each other and this removes the “blocky” appearance present in the 5th percentile data. Analysis of the maximum runoff plots (Figure 5.3) indicates similar patterns for all three though the 95th and, especially, the 99th percentiles were quite “blocky” and again showed streamflows that were too extreme to be representative. Therefore the 90th percentile was selected as the most appropriate indicator for periods of highest runoff.

The absolute runoff analysis, discussed above, gives an overall picture of the runoff patterns over the period of available data showing the seasonal changes in runoff especially on a year to year basis. However, the use of absolute runoff values only allows comparison between rivers visually and patterns from basins of significantly different magnitudes cannot be easily assessed. Relative runoff values were developed to provide a stronger representation of longer term periods of higher or lower runoff anomalies between basins of different sizes and to emphasize similarities in the decadal patterns over the entire period of study. Relative runoff values were developed by dividing each absolute runoff value by the mean value for runoff on that Julian day in the appropriate record. Relative runoff values can therefore be defined as average, below or above average for the period of record. The display of relative runoff plots was designed to remove the average runoff values from the visual interpretation by assigning them as white background so that the high and low runoff periods are more prominent (Figure 5.4). Since each river can be plotted using the same relative scale it makes it much easier

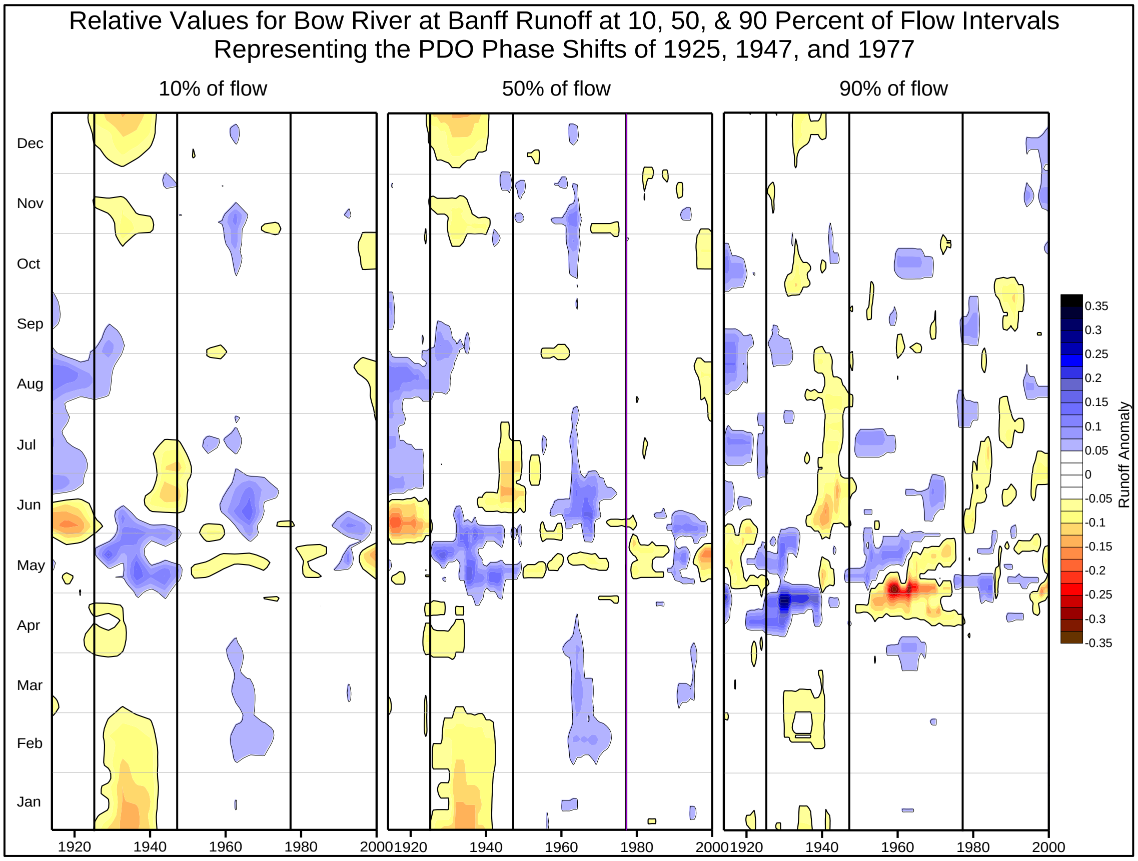

Figure 5.4: The relative runoff values for the Bow River at Banff for the 10th, 50th, and 90th percentiles represented by one scale. The black lines through the plots delineate the 20th century PDO phase breaks.

to compare changing runoff patterns through time between different rivers regardless of basin size. A second dynamic spreadsheet was set up with the relative values so that different percentiles (again for 10, 50, and 90 percent of flow) could easily be analyzed. When comparisons between basins were made the relative and absolute plots were developed using the same period of record to ensure compatibility.

5.2.1 Plotting the visual interpretations

Microsoft Excel was used as an analysis tool because the data could be transformed into a representation that could be easily transferred into the chosen visual analysis program. An EXCEL spreadsheet was set up as a plotting page with the horizontal coordinates being the year and Julian day and the discharge values being mapped as "relief" over the surface. These data were used to create visual representations in the software Surfer 8.

Golden Software Inc.'s Surfer 8 software is a powerful yet easy to use 3-D surface mapping tool (Yakar, 2009) which made it a prime candidate to develop a visualization of streamflow data. Surfer 8 allows for the transformation of up to a billion input points of *xyz* data into contour and surface maps which can be imbedded with colour to make them visually appealing (Yakar, 2009). Version 8 was the most up to date version available at The University of Western Ontario and, as neither of the two later versions contained additions that would be used in this study, Surfer 8 was deemed appropriate for use in this thesis. When the streamflow data were organized in Microsoft Excel into year values (*x* coordinates), Julian date values (*y* coordinates), and runoff values (*z* coordinates - relief) they were transferred into a Surfer Grid using the *xyz* configurations. The Surfer 8 program could then map the "discharge" surface as relief in either 2 or 3 -dimensions. After looking at images created by Dr Chris Smart of the Thames Valley Watershed produced in both 3-D and 2-D it was decided that a 2-D representation of the data would be optimal for this project. The goal is to create a visual technique that is appealing to the eye but is not too cluttered with information, hence the selection of a 2-dimentional surface. To create this 2-D "discharge" surface different colour schemes are added to represent different runoff amounts. Several Surfer plots were generated by changing the flow percentage values or type of data (absolute value vs. relative value) in the same Excel workbook. When plotting the values in Surfer, gridding of the data uses a Kriging filter. This is an adaptive filtering method used to create a trade-off between smoothing an image and blurring its edges (Pham & Wagner, 2000). As well, Kriging minimizes the variance of estimate error by only smoothing when variance between pixels exceeds a set threshold (Pham & Wagner, 2000); in the case of this study the standard Surfer thresholds were utilized.

Two colour schemes were developed to represent the data. A rainbow pattern of red through to purple was developed to represent the gradual change in the absolute runoff value scales for each of the percentile plots (see Figures 5.2 and 5.3 for representative examples of this colour scheme). If a single scale is used that covers the full range of values, the patterns and trends in the 10th and 50th percentile plots are masked which is counter to the goals of this visualization exercise. Therefore comparative plots of

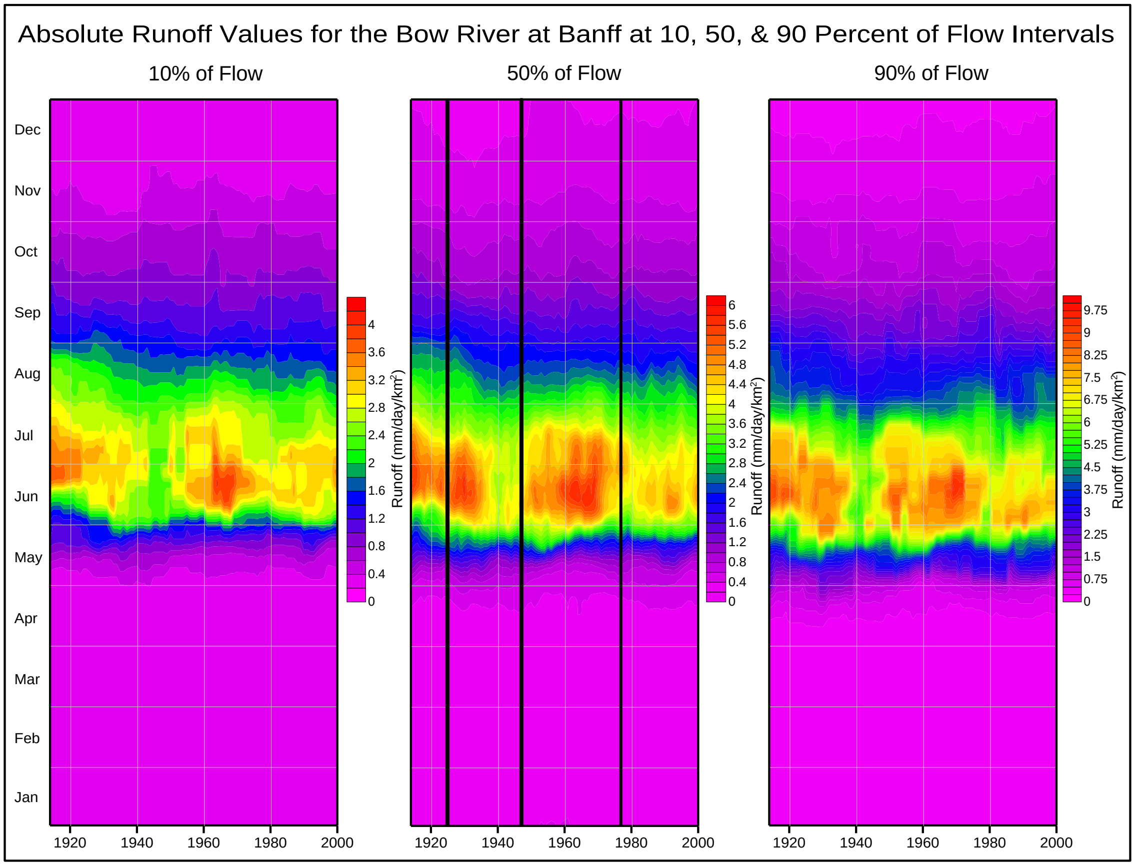

Figure 5.5: The absolute runoff values for the Bow River at Banff for the 10th, 50th, and 90th percentiles represented with separate scales. The black lines on the 50% of flow plot delineate the 20th century PDO phase breaks.

variation in the patterns of maximum, median and minimum runoff use the same colour scheme but scaled to the range of values for the selected parameter, adjusting the range of values in each individual plot (see Figure 5.5). When plotting the relative runoff values a colour scheme of dark blue through to dark red was used with the central values left white so as to emphasize the extreme values that represented the overall decadal patterns in the streamflow regimes. Since the relative runoff plots are comparable across each percentile and each river only one range of values and the same scale is required (see Figure 5.4).

5.3 Analysis of streamflow patterns in the surfer visualization plots

5.3.1 The Bow River at Banff

The Bow River at Banff has the longest record and therefore was used to demonstrate the new visualization technique and to select the level of smoothing, aggregation and colour schemes for this study. After various trials, plots were created for the daily 10th, 50th, and 90th percentile ranges for both the absolute and relative runoff values (Figures 5.5 and 5.4 respectively). Figure 5.5 shows the pattern of absolute runoff values for the low streamflows (10th percentile), median and high streamflows (90th percentile). All three diagrams show a similar annual pattern typical of high elevation basins that can also be seen in the annual hydrograph (Figure 3.4). The period of November through April tends to have very little runoff as many high elevation rivers are frozen at this time. Spring runoff shows rapid increases in May and early June as the volume of runoff increases. Higher spring pulse intervals can begin in early May which is evident in the 90th percentile plot. There is a rapid increase at all three levels of flow characterizing the rapid rise in runoff in spring when melt begins to occur in the headwater basin contributing water quickly into the river system. In contrast the recession to winter runoff conditions is much more gradual occurring throughout the months of August to November. The higher streamflows are sustained though June and July and then decrease with moderate baseflows continuing to be maintained throughout August. These patterns match those seen in the annual hydrograph indicating that this visual representation of the annual pattern is a realistic surrogate of the runoff pattern in the Bow River. However, a major advantage of this visualization technique is that it shows the data for each year in a single plot allowing the identification of trends and changes over time during the period of record. This would be much more difficult using traditional methods that would require multiple graphs to show the same information.

The most prominent feature of Figure 5.5 is the changing characteristics of the high spring/summer runoff periods (shown in red on the plots) over time. The median flow record shows highest summer streamflows from ca. 1915 to the 1930s and during the 1950s through the 1960s. Between these two periods there were particularly low summer streamflows during the 1940s. More recently the average runoff values have not been as high (in the yellow-orange range with no red) but may be trending to another increase after a lower runoff period in the 1980s. These changes are clearly related to the 1947 and 1976 shifts (vertical lines in Figure 5.5, 50% of flow). Although the changes are "smeared" due to the "boxing" of the data, the effects of the "shifts" in 1927, 1947 and 1976 are clearly seen in all three plots of Figure 5.5. Moreover, the nature of the changes (higher summer streamflows see Figure 3.4) is clearly apparent. There are also more subtle changes that can be seen in these plots e.g. there is clearly a trend to earlier spring runoff and an equivalent earlier summer reduction in flows from ca. 1920-1940, particularly for the 10% and median plots. Also the period of moderate summer runoff (green area in the plots) appears to be longer in the median and low runoff diagrams over this period. Over the remainder of the record there is little change in the length of the summer runoff period. However there is some variability and trends in timing of onset and recession from higher runoff (blue/green boundary) mirror the changes in Figures 3.29-3.30.

The major advantage of these annual runoff plots over the traditional graphical methods is that a more complete data set can be seen in one image rather than reviewing individual or averaged annual hydrographs. However, individual extreme events and abrupt changes are not well captured as the focus is on identifying more gradual changes. Given the nature of these data the statistical significance of the trends in the visual plots cannot be tested though the plots provide a useful overview of changes in the basin over time. These diagrams show past changes and comparison with current trends can assist prediction of future runoff. For example by reviewing Figure 5.5 policy analysts can identify the low runoff period of the 1940s followed by much higher runoff in the 1950s Another low runoff period can be identified in the 1980s although it was neither as long nor as low as the earlier event. Therefore an idea of the duration and range of low streamflows can be observed and expectations for future low runoff periods can be based on these past examples and proper planning for potential similar future situations can be implemented. Thus visual appraisal can provide the basis for a more quantitative, statistical review of key periods using traditional methods.

The relative runoff plots for the Bow (Figure 5.4) allow for a comparison over time of decadal scale changes. Examination of the three summary runoff measures shows a similar overall pattern, although the 90th percentile shows more extreme events. The predominant pattern shows relatively higher streamflows in June, July and August in the 1910s which shifted slightly later into August and September in the 1920s. The late 1920s through the 1930s show a very strong pattern of lower than average winter (November-February) streamflows that is not repeated in the 20th century. This pattern also coincided with above average low and median streamflows in the month of May and high streamflows in April. In fact late April of the 1930s appears to be the strongest runoff anomaly over the entire study period appearing very strongly positive in the 90th percentile plot. This would indicate high early spring runoff was occurring which is supported by the statistical observation of earlier timing of CT date (Figure 3.7). This may suggest higher temperatures or snowfall providing for higher than average levels of April snow melt but a climate comparison is needed to determine actual cause (unfortunately data for the late 1930s is missing but temperature levels, especially winter temperature, for the early 1930s do appear to be warmer than previous decades, see Figures 4.1-4.3). However, these high streamflows only lasted for a few years before a more average April runoff regime was restored. The largest negative runoff anomaly also occurs in the mid-April to early-May period of the late 1950s to mid-1960s (90 percentile plot). This anomaly is in the “cool” PDO phase which has been observed to have higher winter snowfall than the “warm” phases (Hamlet *et al*, 2005, Mote, 2006) and is matched by the climate data in Banff (Figure 4.11). Therefore this low runoff anomaly is influenced by something other than the higher winter snowfall rates, possibly the observed lower temperatures (Figure 4.10) causing the high streamflows to be delayed until later in the year.

Another pattern that can be observed in the 50th percentile relative runoff plots is in the 1960s there appears to be consistent trends towards higher runoff anomalies spanning several periods (February-April, June-July, October-November). The period since the 1970s has not shown any significant anomalies although the latter half of the 1990s appear to show a trend towards lower than average runoff in spring and summer with higher runoff values in the winter. However, until more data are available to extend this pattern the overall trend cannot be determined.

A discussion of the trends on the Bow River would not be complete without looking at the major decadal scale variations in the relative plots that match up with the different PDO phases (Figure 5.4, black lines on the plots). Very little can be said about the early century “cool” period as only a few years can be displayed using this roving window method. However, the 1925-1946 “warm” phase shows high runoff anomalies in April and May with lower streamflows occurring through the winter period. This is an opposite pattern to the 1947-1976 “cool” phase when low runoff anomalies are clearly evident during the April and May period in the 90% of flow plot. The 1977-2000 “warm” phase does not show much evidence of a pattern to the runoff, however some higher runoff anomalies in April and May are similar to those from the previous “warm” phase, although not as well developed.

The major advantage of these relative runoff plots is in their common scale both between the different percentile plots but also between different rivers (as will be discussed later). These patterns are strongly tied to decadal scale patterns that have occurred on the Bow River which allows an analyst to identify longer term trends than can be viewed on an annual hydrograph. Comparison of runoff data for each day to its average across the record reveals different temporal patterns to those seen in the absolute value plots: the absolute plot scales data with respect to other streamflows in the same year, whereas the relative plots scale data with respect to streamflows on the same day throughout the entire record.

5.3.2 The Athabasca River near Jasper

The plots for the Athabasca River near Jasper are of shorter duration as the 11 year window excludes the 1914-30 record and removes 10 years from the 1970-2005 record restricting the analysis to the 1975-2000 period. The absolute runoff values plots for the 10th, 50th, and 90th percentiles of flow are shown in Figure 5.6. The most evident difference between these three plots is the timing of the spring increases in runoff. The baseflow values (10th percentile) do not consistently increase until the end of May whereas highest runoff (90th percentile) begin at the beginning of May. This suggests that initial spring runoff events occur in May but baseflow does not consistently rise until later. This is also indicated by examining the period of highest runoff. The highest baseflows are seen in July whereas the highest runoff in the 90th percentile plot are found

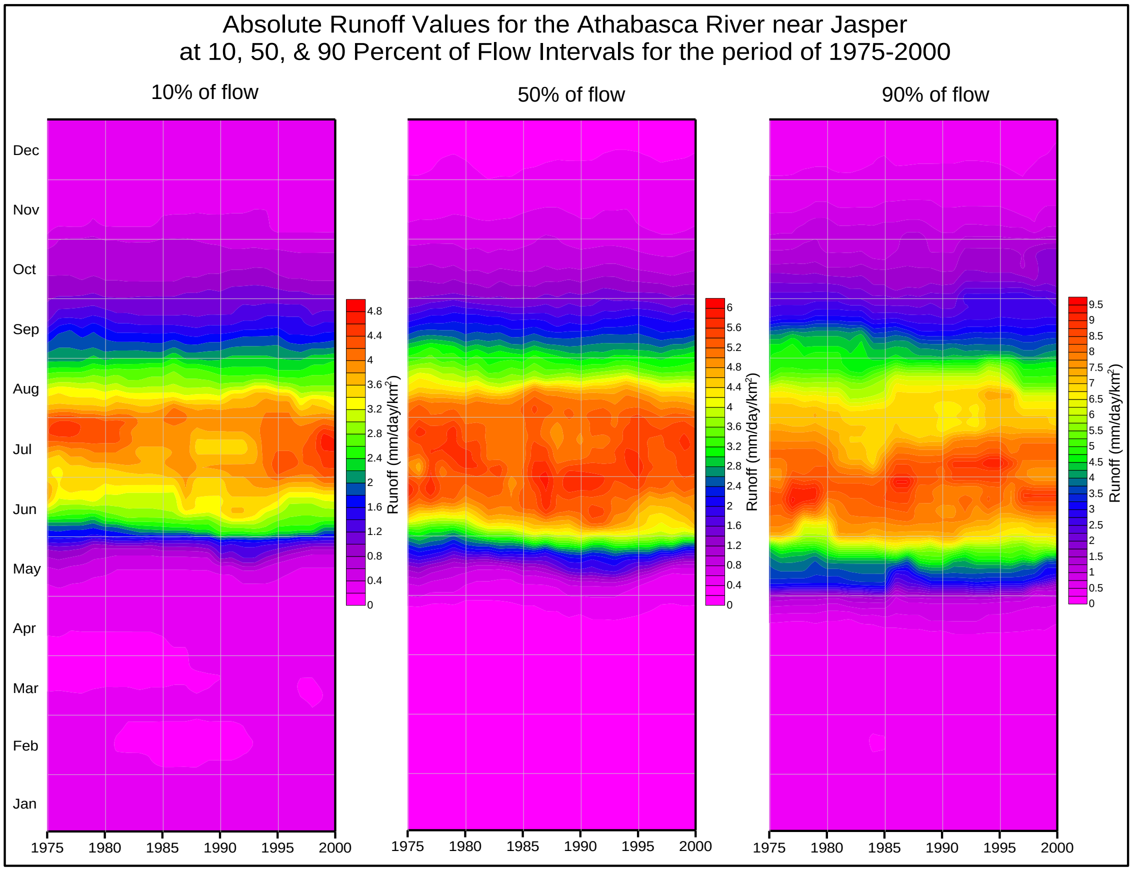

Figure 5.6: The absolute runoff values for the Athabasca River near Jasper for the 10th, 50th, and 90th percentiles represented with separate scales.

in June and early July, again representing the spring melt peaks. This would be expected as greater baseflow values exist following higher runoff events. As expected the median runoff values show the highest values spanning June through August. There is a period in the late 1980s to mid-1990s of lower runoff in the 10th percentile plot which would suggest that less water was available in the basin and baseflows were lower than in the 1970s and late 1990s. The runoff values in the 50th percentile plot do not show any major changes in regime over this relatively short period. The relative runoff value plots for the Athabasca River near Jasper (Figure 5.7) show some decadal scale variability, mainly in the spring runoff period. Lower spring runoff values are observed in the late 1970s until the mid-1980s and in the late 1990s. High spring runoff occur between the late 1980s and mid-1990s. Although the patterns are similar, there are slight differences in the timing and duration of the anomalies between the three runoff levels. Generally the

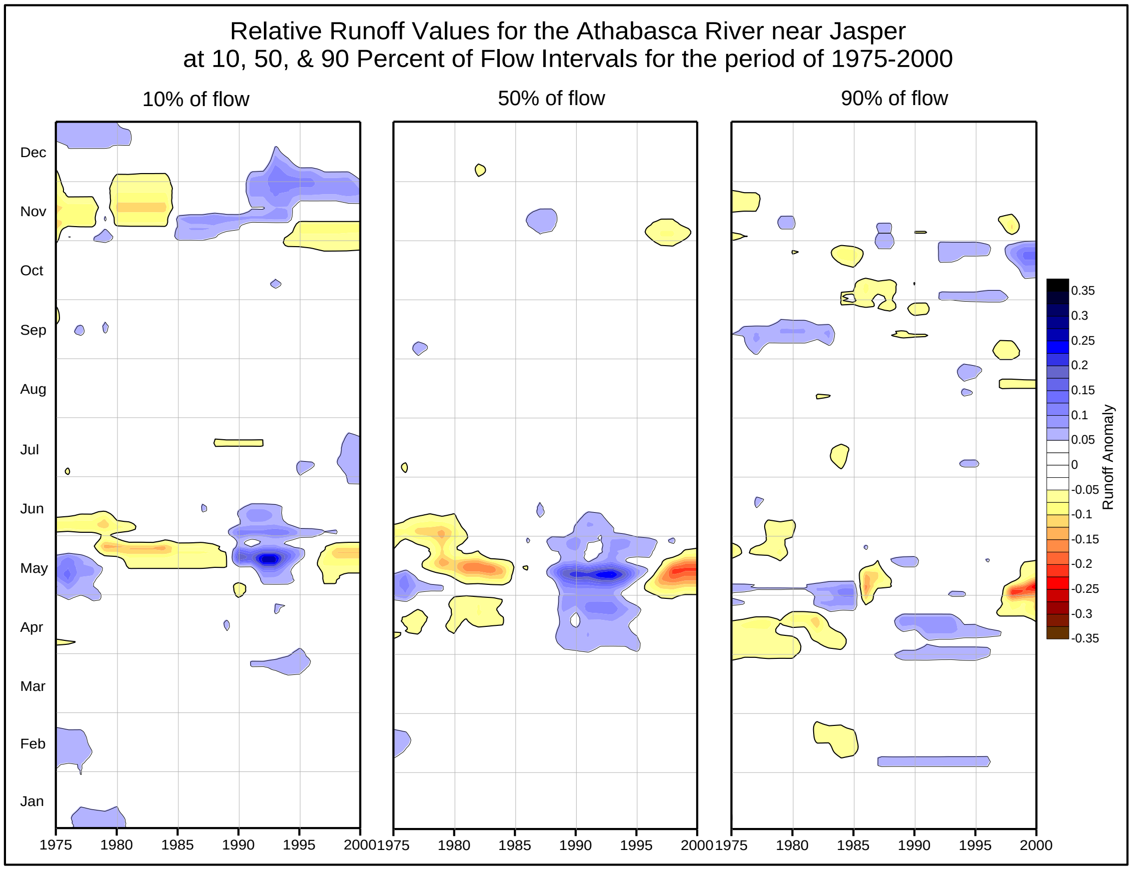

Figure 5.7: The relative runoff values for the Athabasca River near Jasper for the 10th, 50th, and 90th percentiles represented by one scale.

anomalies occur earlier in the highest flows (April – early May) and later in the low runoff data (May and early June). The greatest spring runoff anomaly for this data set is seen in the median runoff values where a major high runoff anomaly occurs from early April to early June in the early 1990s and relatively lower runoff in the 1980s and later 1990s. This indicates decadal scale variability that is not PDO related i.e. it occurs within a single phase of the PDO and would not be as easily seen or possibly masked in a longer record which showed changes due to major PDO-related shifts (i.e. the Bow record). The baseflow diagram (10th percentile plot) also shows anomalies in November with lower values from the 1970s until the mid-1980s and in early November during the second half of the 1990s. It also shows higher runoff in the first half of November during the late 1980s and the latter half of the month during the 1990s. This demonstrates that the late autumn baseflow conditions have been quite variable throughout the last quarter of the 20th century.

The surfer plots of the shorter Athabasca records show runoff variability within a single phase of the PDO but are not as great as those seen in the Bow record which shows evidence of the main PDO shifts during the 20th century. Some trends are visible but the record is too short to indicate whether these decadal scale patterns are repeated within in other phases of the PDO. However, the relative plots can be used for comparison with the Bow Record.

5.3.3 Comparison of the Athabasca and Bow records

With such a short period of record available for the Athabasca River near Jasper no long term trend patterns can be determined. However, if the Bow record is assumed to be representative for this region it may be useful to compare the results from the visualization technique over their common period (1975-2000). Figures 5.8-5.10 show comparative plots of the 10%, 50% and 90% flow levels for the two records with the colour scales adjusted to the runoff volumes in each record[8]. These plots illustrate some

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[8] While the colour scheme remains the same for each scale the absolute value for each colour class differs between plots.

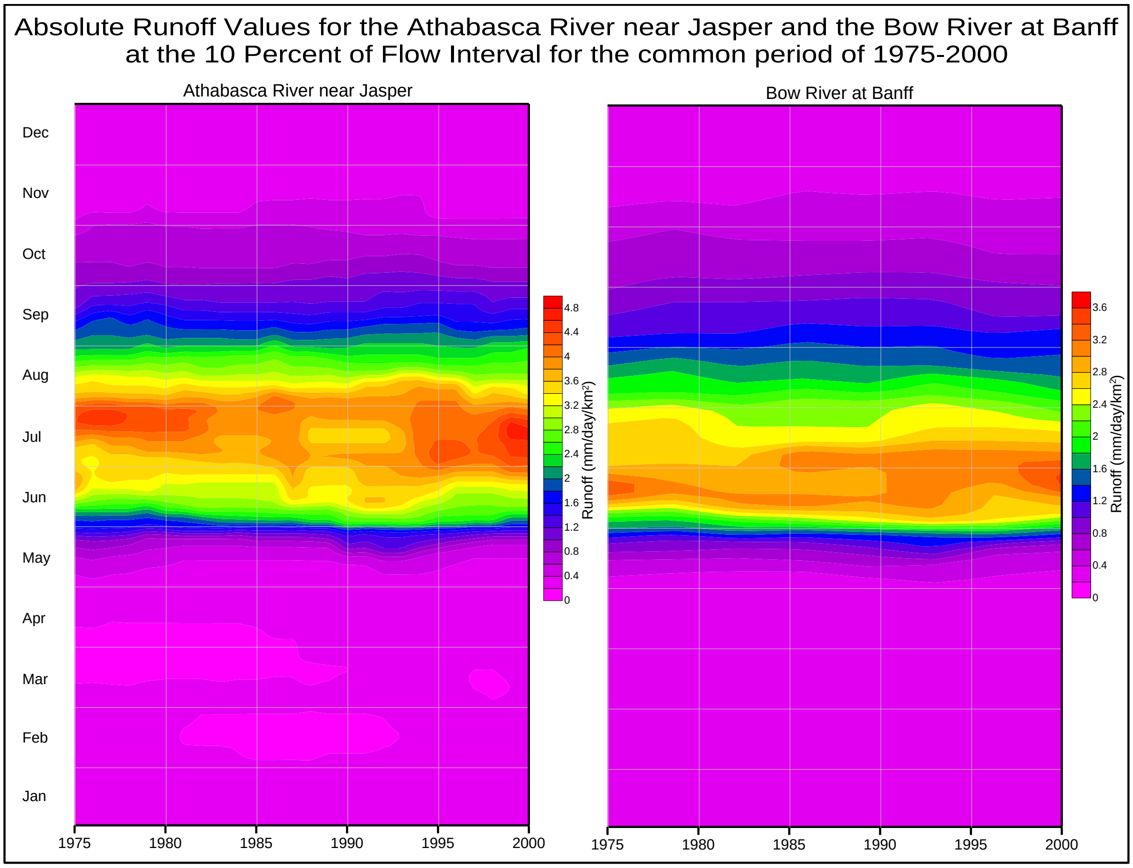


Figure 5.8: The absolute runoff values at the 10th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using separate scales.

differences in the timing of streamflow between the two drainage basins which is a function of several differences between the basins. Although all three figures show similar timing in the inception of higher streamflow in the spring they all indicate that the duration of these levels is longer in the Athabasca Basin. Moreover the duration of the highest runoff on the Bow River is less than half the time of the equivalent runoff on the Athabasca River (Figure 5.10). As well as being larger, the Athabasca basin has a greater glacier cover and a greater area at higher elevations that contribute to a longer and later melt period than that in the Bow basin (see Table 3.1). These factors result in different runoff magnitudes and offset the timing of absolute runoff regimes in the Bow River at Banff and the Athabasca River near Jasper for the period of 1975-2000. However, although the length of the high runoff period is longer on the Athabasca River the general pattern of runoff seen between the rivers is similar. Figure 5.8 shows periods

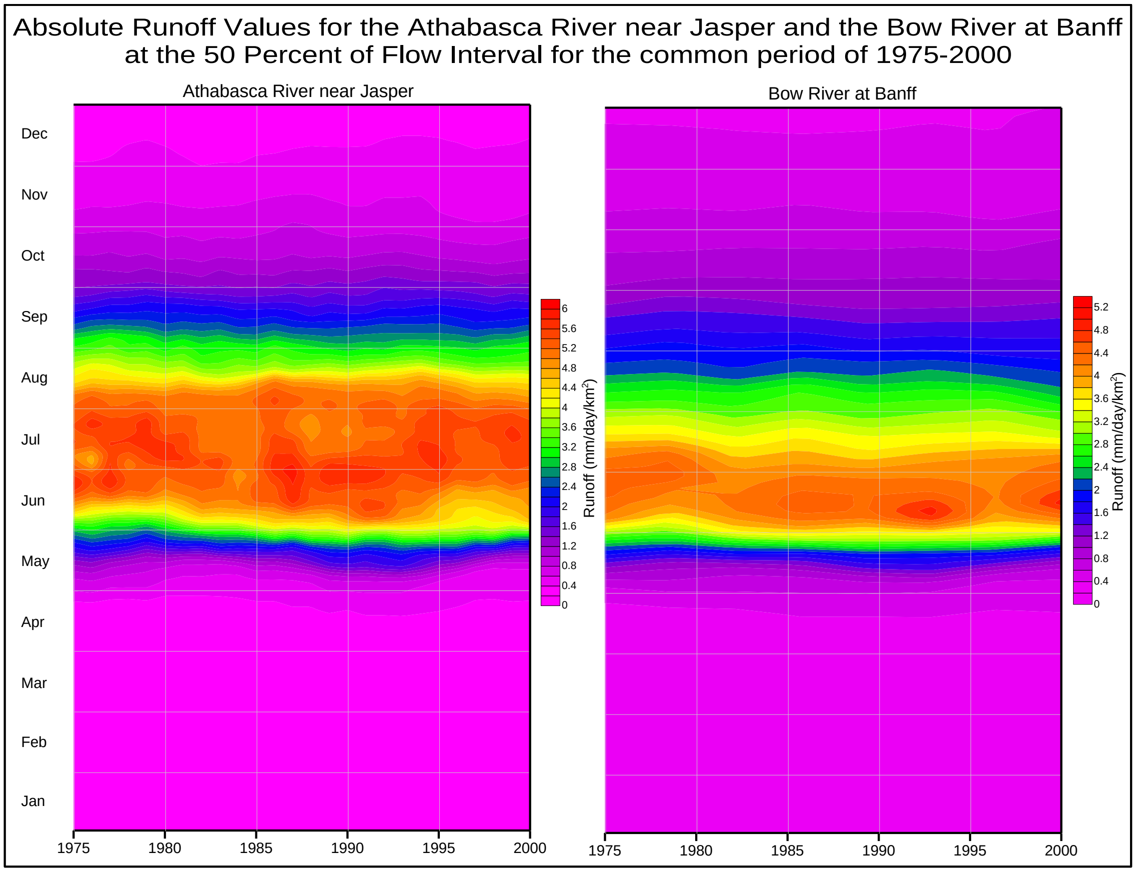


Figure 5.9: The absolute runoff values at the 50th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using separate scales.

of higher runoff occurring at both the beginning and end of the common period on both rivers and similarities are also seen in Figure 5.10, specifically the reduction in runoff ca. 1980 and at the end of the melt season in ca. 1985. While an initial appraisal of the median runoff values suggests they seem quite different, both rivers show similar reductions in high runoff values in the early 1980s and mid to late 1990s. Therefore the absolute values of runoff for the Bow River cannot be used as a direct substitute for the streamflow regime of the Athabasca River as these plots do not indicate strong similarities in the regime magnitudes. However, while not identical there is some similarity in pattern between these two rivers and it is the relative plots which are better used for comparative analysis and they may provide a stronger link between these two sites.

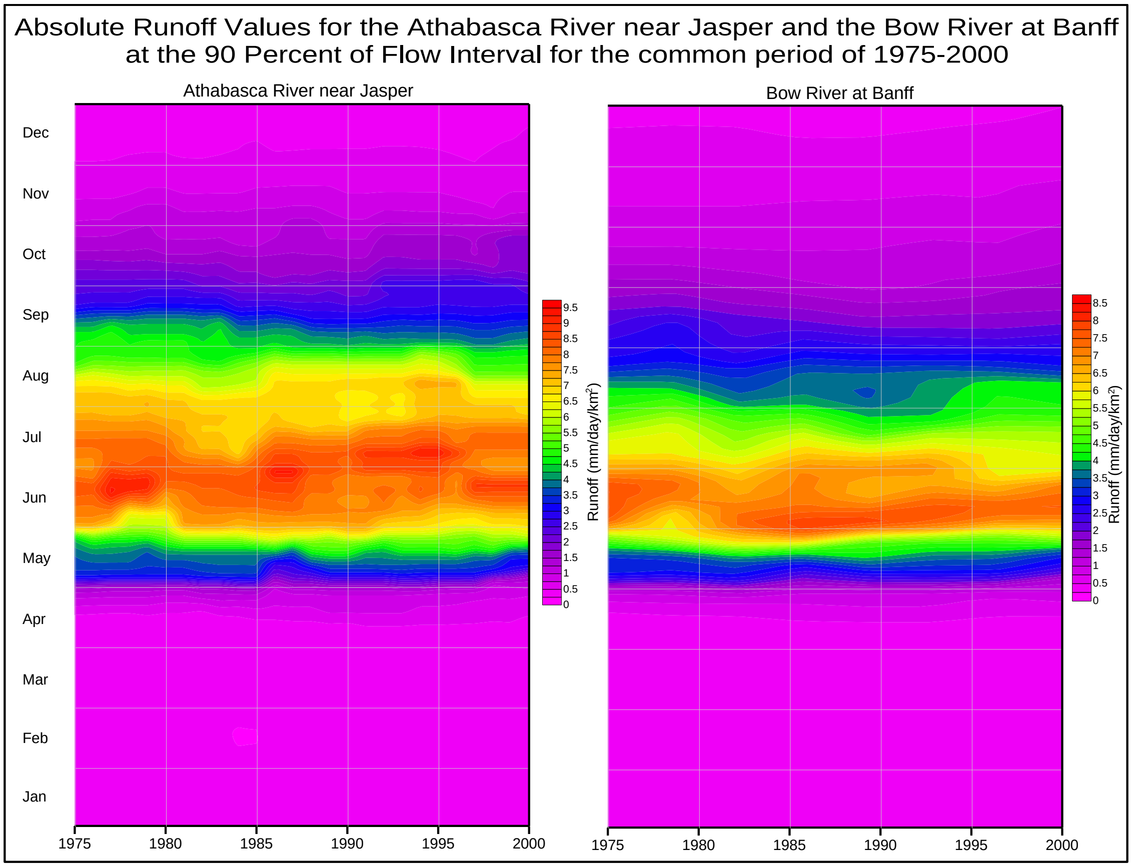


Figure 5.10: The absolute runoff values at the 90th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using separate scales.

The relative runoff comparisons of the 10th, 50th, and 90th percent of flow levels are plotted in Figures 5.11-5.13 respectively. The 10th percentile plot (Figure 5.11) shows that the May-June pattern of runoff seen in the shorter Athabasca record is present, though slightly weaker, in the Bow i.e. low runoff in the early 1980s and later 1990s and higher runoff in the first half of the 1990s. However, the strong variation in fall runoff seen in the Athabasca is not visible in the Bow record and there is a greater variability in the autumn data for Athabasca than for Bow. The strength in the anomalies may relate to the higher magnitude of streamflow volumes that are observed on the Athabasca River. Both rivers show the same spring anomaly pattern in the 50th percentile data with a stronger signal and greater variability of runoff in the Athabasca record. Again, the greater strength of the anomalies in the Athabasca record may relate to the higher magnitude of runoff volumes. The fall anomaly in the low runoff of the Athabasca is not

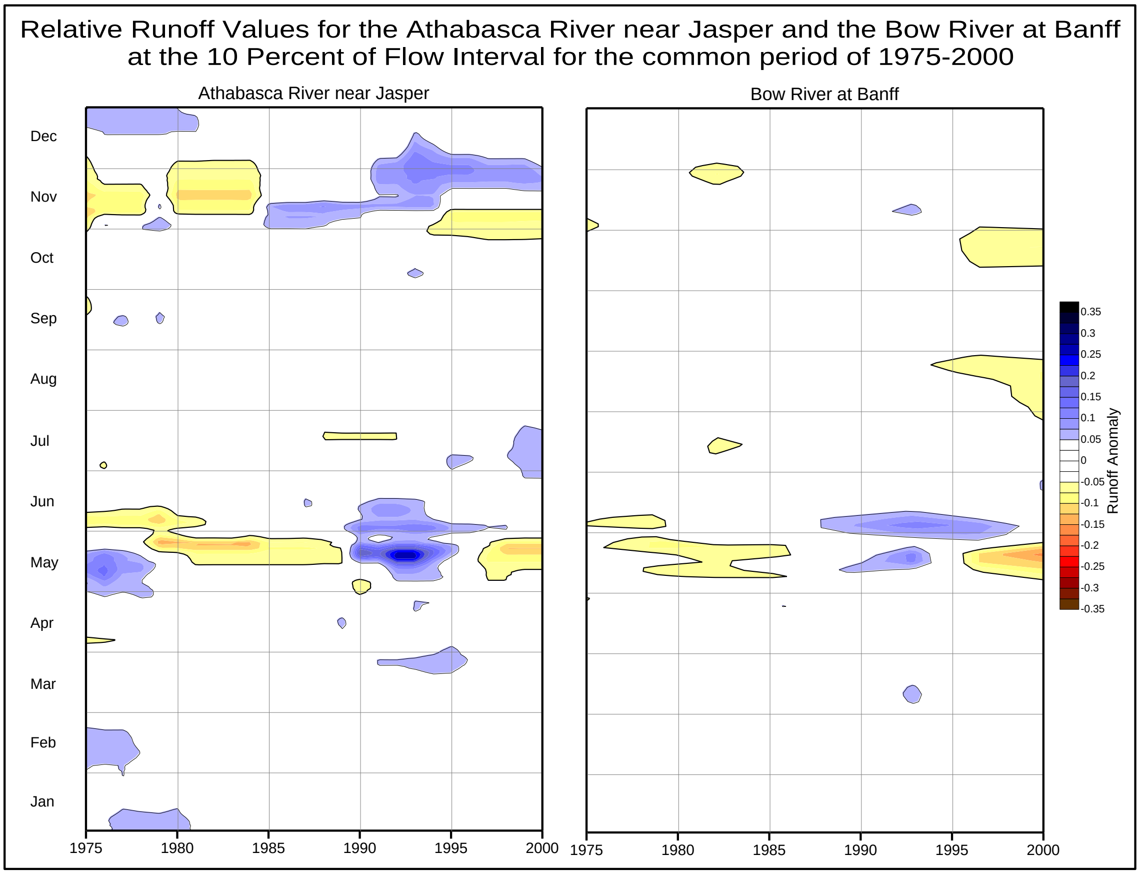


Figure 5.11: The relative runoff values at the 10th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using a single scale.

replicated in the median data. The diagrams for the 90th percentile of flow on the two rivers (Figure 5.13) show considerable variability and few common anomalies, though there remains a more diffused spring pattern.

The relative runoff plots show that the overall spring anomaly patterns are similar between the two rivers but there are some differences in these patterns indicating that the Bow data is not a perfect match for the Athabasca over this period. However, the patterns of runoff changes are quite similar for both rivers and therefore, the general changes in the streamflow regime of the Bow River at Banff could be used to infer the probable changes that have occurred in the streamflow pattern of the Athabasca River near Jasper over the 20th century. The runoff volumes of the Athabasca are higher than the Bow and there is a greater glacial influence but both are responding in similar fashion

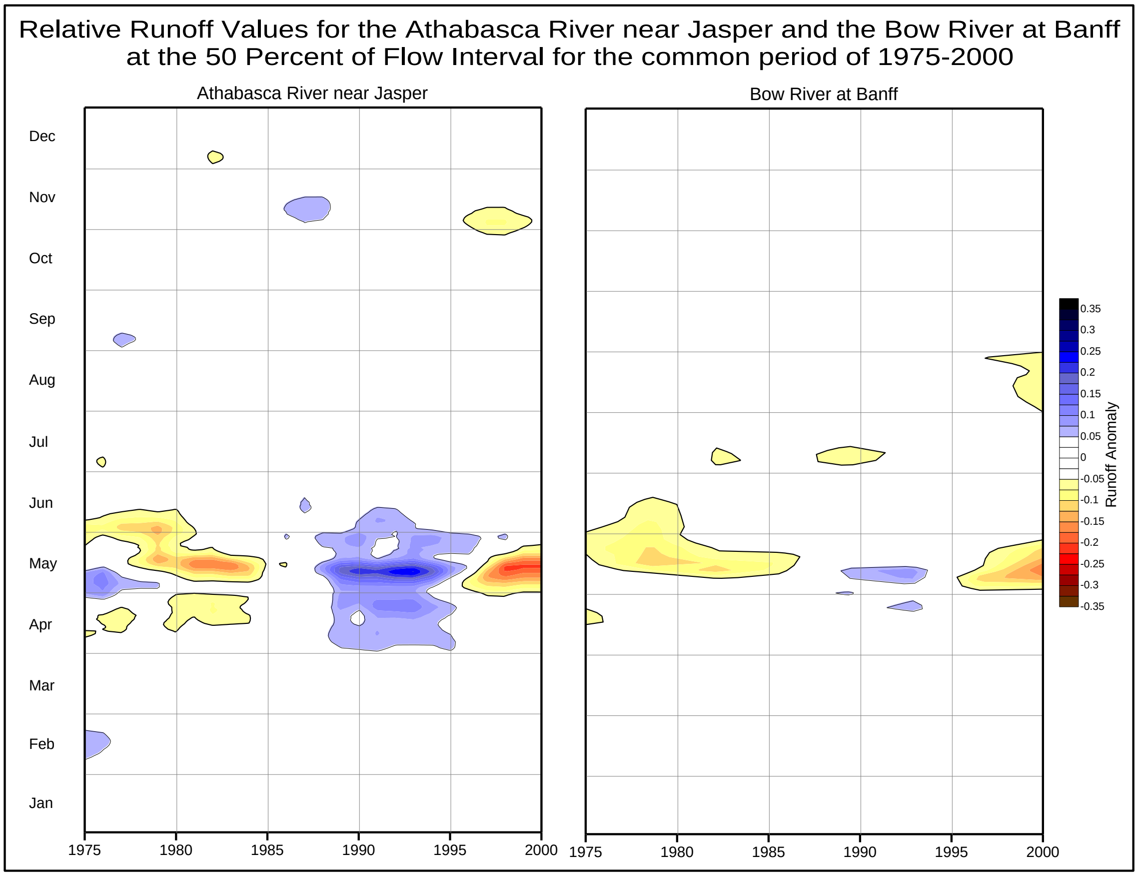


Figure 5.12: The relative runoff values at the 50th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using a single scale.

to overall climatic changes in precipitation and temperatures. The relative runoff diagrams best demonstrate this in the comparison of high and low runoff anomalies in response to spring conditions. Therefore the relative runoff diagrams for the entire Bow record could potentially be used to predict equivalent responses for periods where data were not available for the Athabasca.

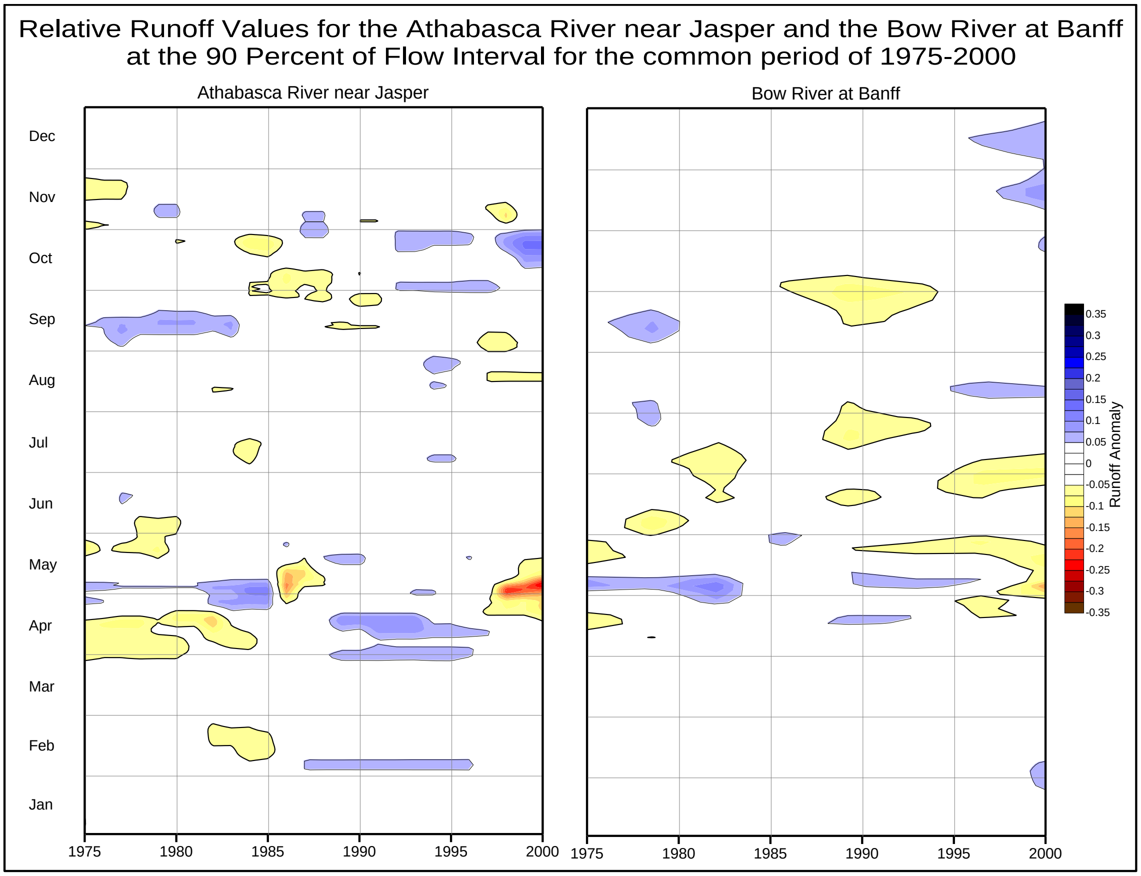


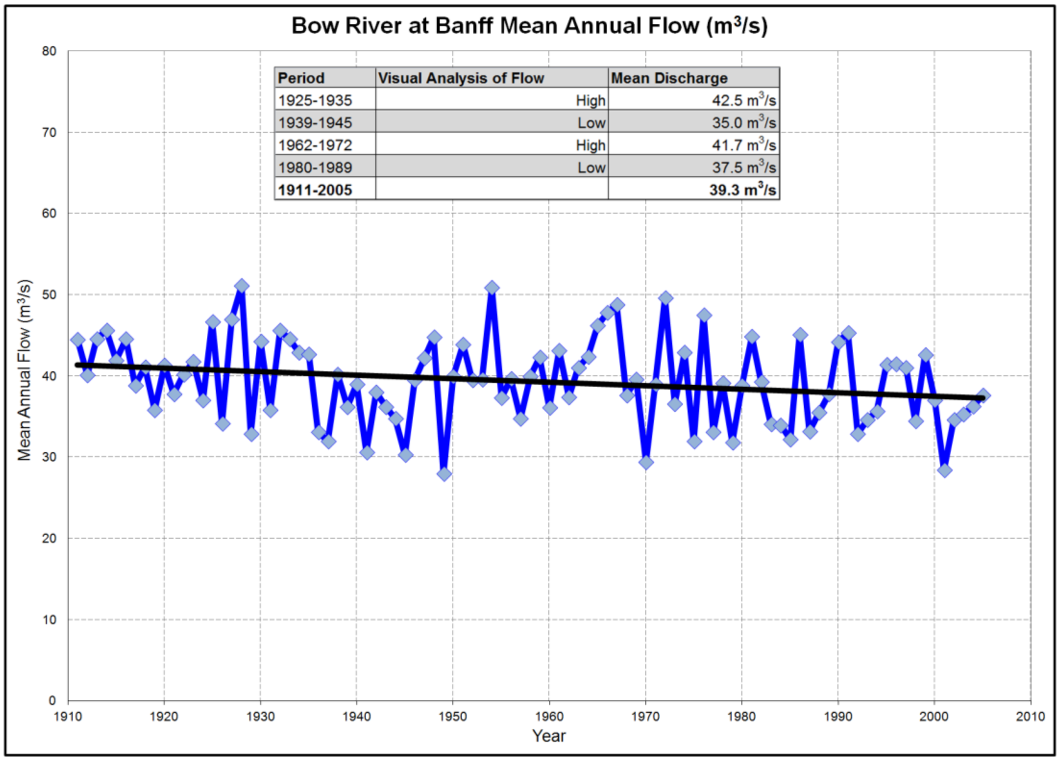
Figure 5.13: The relative runoff values at the 90th percentile for the Athabasca River near Jasper and the Bow River at Banff represented using a single scale.

5.4 Visualization vs. statistical methods: Linking the techniques

This chapter has modified and discussed a visualization technique that was originally developed by Dr Chris Smart but required variation for application to rivers in a mountainous environment. The technique shows changes in the annual streamflow regime of rivers over time. The results from this technique on the Bow River record can be compared to the more traditional hydrological analyses presented earlier. Of the two approaches probably the mean runoff volumes and median runoff diagrams are the most directly comparable between the two approaches. Visual examination of the median runoff values for the Bow River (Figure 5.5) identified four distinct periods in June-July discharge namely high runoff in 1925-1935 and 1962-1972 and low runoff in 1939-1945 and 1980-1989. Figure 5.14 shows the mean annual flow values for the Bow River at

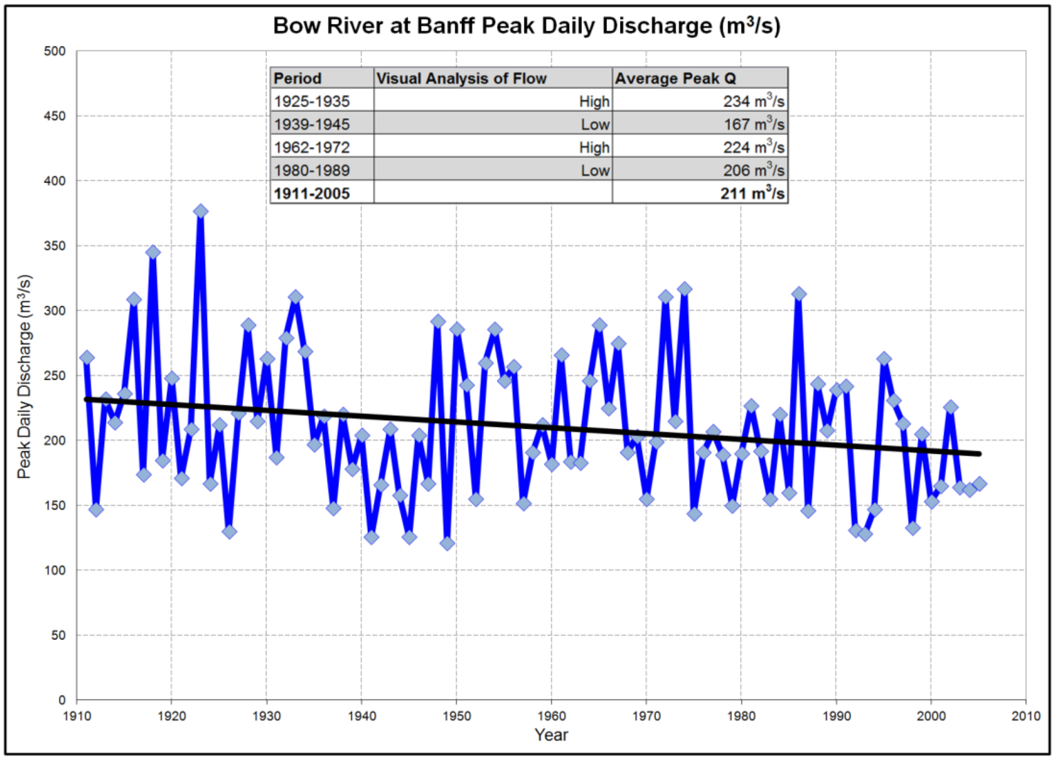
Banff and the table lists the mean values for the four selected streamflow periods (seen in Figure 5.5) from the instrumental record. The periods of high and low runoff identified from the visualization have mean values higher and lower than the 1911-2005 mean respectively. The 1939-1945 period is the most prominent outlier in both the visualization and the mean flow diagram. The peak daily discharge values given in Figure 5.15 also demonstrate that these four periods have mean values above or below the mean of the entire period and the 1939-1945 period is again the most prominent. However, the peak daily discharge values should most probably be compared with the 90th percentile visualization where the two high and two low streamflow periods are also clearly differentiated.

There are also some linkages with the timing of streamflow. Visual interpretation of the Bow absolute value plots indicates several temporal patterns such as the trend to earlier peak discharge from the start of the record until ca. 1925, the rather constant timing of peak flow from about 1945-1970 and the trend to a later peak discharge from 1970-1980.



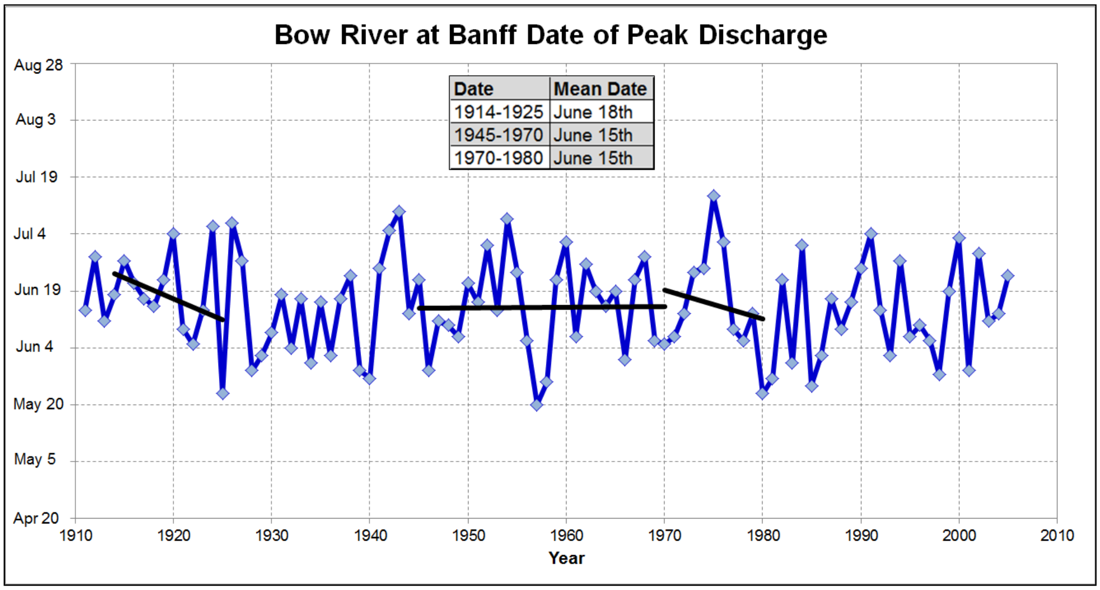
Period	Visual Analysis of Flow	Mean Discharge
1925-1935	High	42.5 m^3/s
1939-1945	Low	35.0 m^3/s
1962-1972	High	41.7 m^3/s
1980-1989	Low	37.5 m^3/s
1911-2005		**39.3 m^3/s**

Figure 5.14: Mean annual flow for the Bow River at Banff.



Period	Visual Analysis of Flow	Average Peak Q
1925-1935	High	234 m^3/s
1939-1945	Low	167 m^3/s
1962-1972	High	224 m^3/s
1980-1989	Low	206 m^3/s
1911-2005		**211 m^3/s**

Figure 5.15: Peak daily discharge for the Bow River at Banff.



Date	Mean Date
1914-1925	June 18th
1945-1970	June 15th
1970-1980	June 15th

Figure 5.16: Date of peak discharge for the Bow River at Banff. The black trendlines are given for the four periods where timing trends were noted in the Bow record surfer plots.

When these periods are compared to the dates of peak discharge (Figure 5.16, black trendlines applied for each of the three identified periods) the trend to earlier peak date at the beginning of the record and the constant trend through 1945-1970 agree. However, the visualization results and statistical analysis do not match for the 1970-1980 period. Peak discharge over this interval does not show a consistent trend to later peak discharge. This demonstrates that whilst the visualization technique is useful for suggesting trend periods over longer intervals, it is not sensitive to shorter period trends as a result of smoothing with an eleven year window. Selection of the window size also limits the frequency of trends that can be identified. Therefore, although the two techniques are complementary, visual analysis cannot directly replace traditional statistical methods. The potential advantage of the visual representation lies in its usefulness for community based participation. A Surfer plot can be presented to a group of people without technical or hydrological backgrounds and they could be shown a complete set of information with the use of just one diagram. Larger studies such as this one looking at more than one measure and/or more than one site would require more than one diagram but it this would still involve less material than utilizing individual annual hydrographs. In order to determine if this technique is useful in community policy participation however, a trial process with community groups would be required. For policy use the visual representation using Surfer allows for large amounts of data to be presented at one time. An analyst could use this visual data as supplementary material to a traditional approach and use it to identify the major trends in the streamflow data visually with fewer graphical representations than more traditional statistical methods. The decadal scale analysis allowed by this plotting technique is also useful to indicate the presence of the PDO influence on streamflow as the effects and occurrence of the PDO are not well known outside a relatively small research community. By comparing the two approaches and looking for differences an analyst could identify information not immediately apparent from either technique, leading to further investigations. Therefore, even though detail of the statistical techniques is lost in the visual plots, the visual analysis should be considered as a supplemental form of information that is useful in streamflow analysis as it provides overviews not found in traditional methods. As well, the decadal scale analysis allowed by this plotting technique is also useful to indicate the effects of the PDO on streamflow regimes.

5.5 Conclusions

Application of this visualization technique was explored to see whether it could provide an alternative or complementary analysis to the traditional statistical methodology in hydrological analyses. However, it is not a replacement for traditional methods. Conventional statistical analyses have several advantages that cannot be duplicated by visualization techniques (e.g. quantitative determination of trend or statistical significance). Nevertheless, visual representation may have merit and a place in hydrological study as a complimentary tool. For an expert who is familiar with statistics and is well trained in trend analysis a visual plot may not provide additional insights although such representations can provide a compact overview of the entire dataset leading to subsequent statistical applications (e. g. Fig 5.5 clearly illustrates some of the PDO-related shifts and differences in streamflow regime over the 20th century). The two approaches can complement each other to provide a better result. The other key use of this technique is for presentation of data to individuals without a hydrological background. Social pressures are making community based participatory planning more common (Pahl-Wostl, 2002) and often policy analysts must present their data to groups with no statistical or quantitative expertise. Presenting such data visually may make the information more accessible and less intimidating to those involved and therefore assist in getting complex ideas across (Sadie & Getz, 2005) and easing communication between analyst and community as it would introduce the information in a manner that is more user friendly than statistics and numbers. The technique developed in this chapter could have a place in hydrological analysis although it does have limitations. It appears to work best with longer data sets such as the Bow than with more fragmentary data like that of the Athabasca (similar to traditional methods). Extreme event identification is not possible due to the smoothing required for useful presentation. However, the visual representation can be used to identify decadal scale trends, especially using the relative data, to indicate streamflow anomalies that are an important focus for hydrological study. Further research is required to determine the overall usefulness of visualization as a technique for the presentation of complex data. The two data sets used in this study only provide a preliminary trial using a small sample of available streamflow data. This future work could be undertaken using data from other sites in the southern Canadian Cordillera which is readily available.

Chapter 6

6 Conclusions

6.1 Conclusions of this study

The primary goal of this thesis was to evaluate the hydrological records of the headwaters of the Athabasca and Bow Rivers in the southern Canadian Cordillera. The gauge record for the Bow River at Banff is the longest natural streamflow record in the Canadian Rockies and had not been analyzed in detail previously. Although the record for the Athabasca is much shorter, it has not been analyzed and is an important headwater tributary of the Mackenzie system. Moreover, analysis of the Miette River and Sunwapta River at Athabasca Glacier, both headwater tributaries of the Athabasca, allow analysis of the importance of glacier input to the discharge of these alpine systems. This analysis used Daily HYDAT data for the Bow (1911-2005) Athabasca River near Jasper (1971-2005), the Miette River near Jasper (1976-2005) and the Sunwapta River at Athabasca Glacier (1951-1996) plus Environment Canada's Historical Climate data of precipitation and temperature for Banff (1911-2005) and Jasper (1918-2005). Previous work had demonstrated the important control of the PDO on hydrological regimes in western North America (e.g. Moore & McKendry, 1996, Hamlet *et al*., 2005,) and also noted important changes to earlier dates of spring peak discharge due to climate warming (Mote, 2006). The more detailed analysis of records for the Rockies, primarily for the long record from Banff, demonstrates the relative importance of these controls.

The PDO is the leading principal component of North Pacific monthly sea surface temperature (SST) variability (Mantua *et al*., 1997) with an event persistence of 20-30 years (Mantua & Hare, 2002). The primary effects of the PDO seen in the Banff and Jasper climate records are related to the regime shifts noted in 1925, 1947, and 1976 during the 20th century (Mantua *et al*, 1997). These show increasing annual and winter temperature trends with lower mean temperatures and increased winter snowfall from the 1947-1976 "cool" phase and decreasing annual and winter (very minimal) temperature trends with higher mean temperatures and decreased winter snowfall from the 1977-2005 "warm" phase are most clearly seen in the longer Banff climate records but also are present in the Jasper data. These PDO effects are seen in mean annual and summer discharge of the Bow River with greater discharge during the "cool" phases and lower streamflows during the "warm" phases. Decadal scale variability in the hydrological data are found in the "cool" phase (1947-1976 phase only) of increased mean annual flow, increased peak daily discharge, and later CT timing and decreased mean annual flow, decreased peak daily discharge, and earlier CT timing during the 1925-1947 and 1977-2995 "warm" phases on the Bow Record. The Athabasca record only contains data for the post 1976 phase but the hydrological variables in this period show similar trends to those observed in the Bow 1977-2005 record although none of the Athabasca trends are seen to be significant. The seasonal (June – September) streamflow regime of the Sunwapta River in the Athabasca basin does show changes related to the 1976 regime shift, with the most evident PDO connections seen in the volume and timing of peak and to a lesser extend the timing of CT date. However, the strength of these relationships is not nearly as strong as in those of the long annual Bow record.

This long, continuous Bow record was the best option for hydrological analysis in this study for, although the greatest evidence was related to the PDO, some long term trends stood out above the multidecadal variability. There were significant decreases in streamflow volumes as well as significant changes to an earlier timing of CT date over the 1911-2005 period. Unfortunately the Athabasca record is too short to show these effects but there is sufficient evidence from the Jasper climate record and limited hydrological data to infer that, over the 20th century, there have been similar regime changes in the Athabasca basin to those seen in the longer Bow record. i.e. a similar pattern of changes to those seen for the Bow would be expected in the 20th century discharge of the Athabasca, though the magnitudes would be different.

The effect of glacial melt contributions was also examined through evaluation of discharge records for the Miette, Bow, Athabasca, and Sunwapta Rivers. These rivers have respectively ca. 0.2%, 3.3%, 8% and 61% glacier cover. Analysis of the May through October daily streamflows for all five rivers over the common 1976-1996 period showed progressively later median flow dates of June 29 for Miette, July 9 for

Bow, July 18 for Athabasca, and July 28 for Sunwapta (Figure 3.24). There are also considerable differences in the duration and timing of summer high streamflows showing that the rivers peak in early June on the Miette and Bow, late June to early July on Athabasca and late July and early August on the Sunwapta (Figure 3.25). Although these records do not illustrate significant changes in a single stream system through time they do indicate the likely regime changes that can be anticipated as future glacier cover progressively disappears.

A secondary goal in this thesis was to implement and develop a visualization technique that would be an alternate option to traditional statistical analysis. These visual representations summarize the complete streamflow record in a single diagram and can be used as a tool to analyze multidecadal variability and permit easy visual understanding for those without a statistical background. Although they cannot replace traditional methods they allow a complementary approach which has some advantages. Large groups of data can be displayed on one figure which allows easy interpretation for data that would normally involve large numbers of annual hydrographs viewed on separate plots. Figure 6.1 represents the absolute runoff values for median flows on the Bow River at Banff which is well suited to showing decadal scale trends in one representation. This decadal scale pattern is linked to the PDO and changes can clearly be seen following the main 20th century PDO shifts (black lines at 1927, 1946, and 1976 in Figures 6.1 and 6.2). The relative runoff plots (Figure 6.2) are also valuable to compare basins of differing magnitudes and sizes. As with the statistical methods, visualization is most effective with larger data sets but patterns are shown for the shorter Athabasca data set (1976-2000) that demonstrate changes within the 1977-2005 phase of the PDO. While expert hydrologists may not see a need to add such visualizations to their repertoire of techniques it has strong appeal for community participatory planning processes where the group being introduced to the data does not have a statistical background. Using fewer and bright and interesting diagrams like those developed here would allow explanation of the data in a much more inclusive manner.

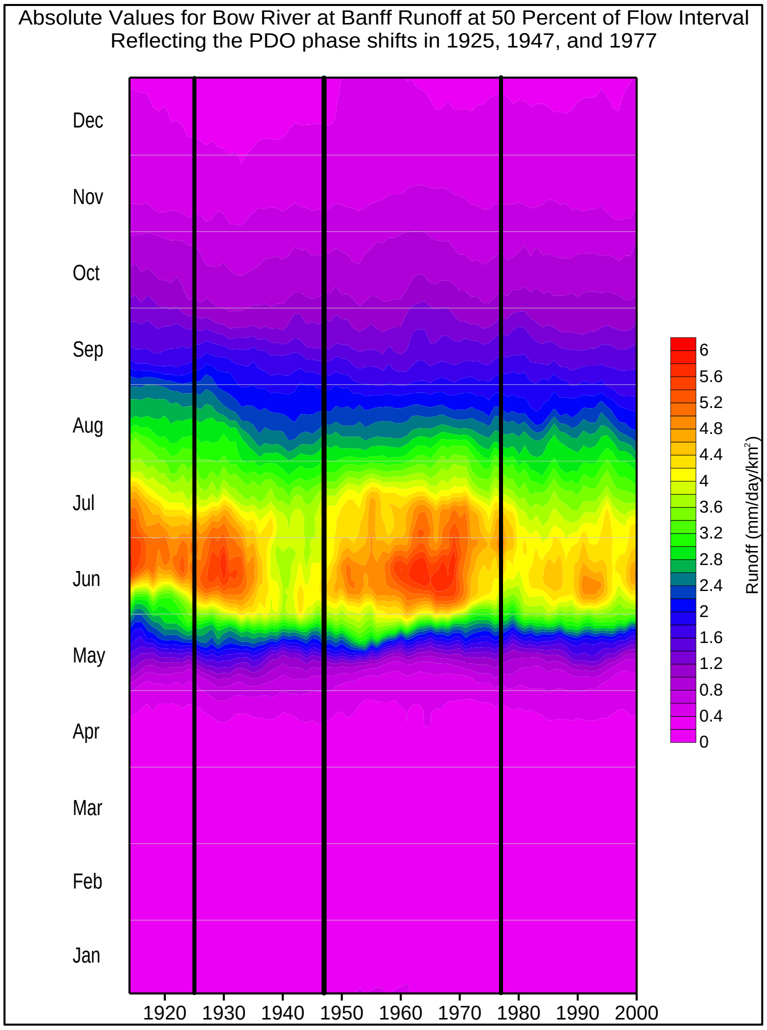


Figure 6.1: Visual surfer plot of the absolute values of Bow runoff at 50% of flow demonstrating the changes related to the PDO phase shifts.

6.2 Future Work

This research has involved specific data sets from Environment Canada's HYDAT database. Further research to confirm the findings of this research could be undertaken using other streamflow data available in this area. Specifically, the effect of glacial cover, the evidence of the PDO, and the potential usefulness of the visual technique could be tested using the data from the downstream records of the Athabasca watershed and to other watersheds in the area that have not yet been studied which have records long enough to run statistical analysis. This would allow for the trends observed on the rivers in this study to be compared to surrounding areas to determine what local conditions are

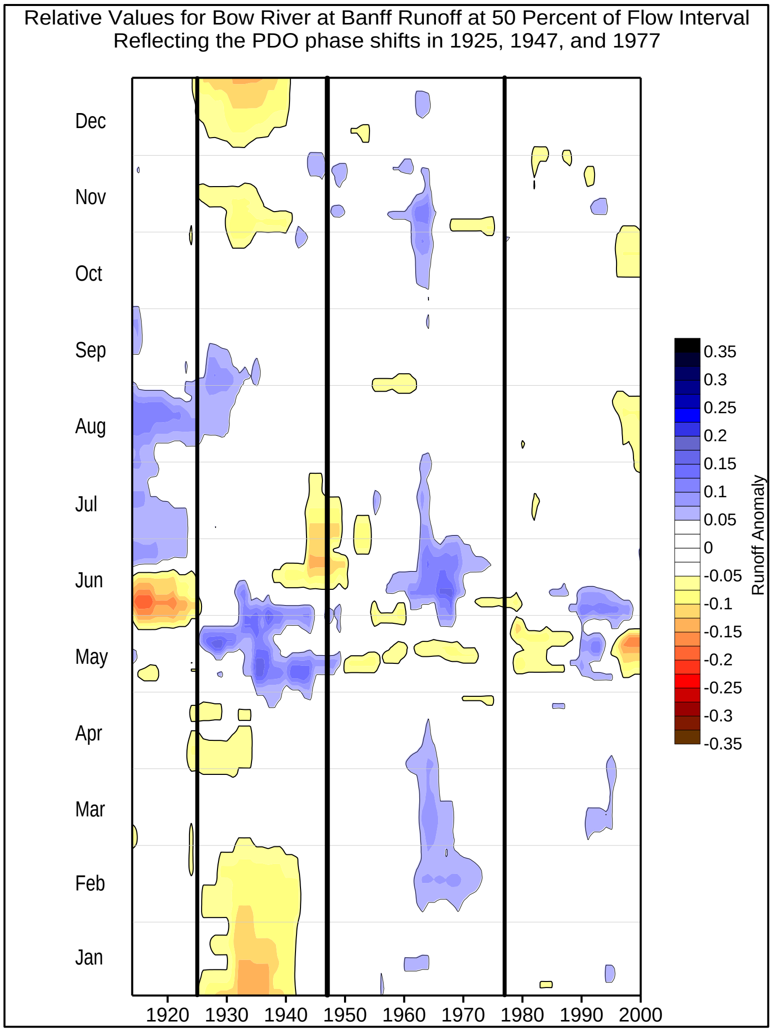


Figure 6.2: Visual surfer plot of the relative values of Bow runoff at 50% of flow demonstrating the changes related to the PDO phase shifts.

having on the overall regionally expected pattern dominated by the PDO. Expansion of the use of the visual technique into water policy and planning could also be beneficial as this could determine if it had merit in application rather than just in hypothetical feasibility.

The research undertaken in this project has demonstrated some very valuable patterns of change in the hydrological regime in the southern Canadian Cordillera. Analysis shows that, possibly PDO effects have so far overridden long term changes in climate warming so that there are not the clear patterns seen in previous studies undertaken in the western

United States (e.g. Dettinger et al, 2004, Stewart et al, 2004, 2005, Rood et al, 2005, Hamlet et al, 2007). Application of these results to water policy would allow for an improved knowledge base and the potential to better predict and plan for future water availability in the study regions.

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