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Hydrologic Risk Assessment Framework for Alberta's Green Zone

by

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Abstract

In this dissertation, a hydrologic classification approach was tested using the shape factor of hydrographs to represent variation in streamflow regimes across Alberta. Hydrograph shape factor was effective at separating the forested landbase into 6 spatially distinct regions. Further statistical analysis of hydrometric data showed each region to have unique streamflow characteristics. Differences in physiography between regions were evident and strong associations were found between physical catchment characteristics and hydrologic variables describing streamflow magnitude and timing. In a case study, findings were used to define the regional natural range of hydrologic variation and applied into a watershed assessment tool evaluating the potential changes to streamflow regimes as a result of forest disturbance. This analysis showed that because of hydrologic variability among regions, spatial variation in sensitivity to harvest likely exists within the forested landbase, highlighting the need for development of regional criteria and indicators for sustainable management of water resources.

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Chapter 1: Introduction

1.1 Forests and water resources management

Approximately 10 percent of the world's forests are located in Canada, 93 percent of which are located on crown owned land and managed by federal and provincial governments (CCFM, 2006). One of the most important benefits of forested lands, other than timber, is an abundant supply of water. Forests are an essential component in the water cycle and are important in the protection and supply of clean water. The importance of clean, safe water cannot be overstated as 88 percent of Canadian municipalities obtain their drinking water from surface water sources (Environment Canada, 2007), a large proportion of which originates from forested lands. In Alberta, water security issues are of paramount concern to the public who are faced with a drying climate and ,in some basins, moratoriums have been placed on water licences for domestic, industrial and agricultural use (Alberta Environment, 2006). Increasing populations and demand of land for development are primary stressors on Alberta's water resources. Fuelling public concerns over water, the extraction of natural resources across Alberta's forested lands (the green zone) are resulting in greater public involvement in land management decisions and development of policies aimed at source water protection. The disturbance of forests by resource extraction (e.g. petroleum development and timber harvesting) can have significant impacts on water quality and quantity, occurring through alteration of the hydrologic processes within the catchment. Forest disturbance can alter water quality and cause changes in the timing and magnitude of peak flows, base flows and total annual water production (yield) (Bosch and Hewlett, 1982; Stednick, 1996; Swank *et al.*, 2001).

Most forested land in Alberta is managed by the crown and the people of Alberta rely on government agencies to assure that water resources are being protected during resource extraction activities. Currently, public and government agencies are struggling to determine the appropriate levels of forest disturbance that should be permitted in a watershed or region before negative impacts indicate an unacceptable change to the hydrologic processes (CCFM, 2006). The definition of 'negative impact' and 'unacceptable change' remains unclear in forest management research and both terms continue to be vaguely defined in forest management policies.

In Canada, the way that forests are being managed has changed from a movement away from an era of sustained yield of timber to one of sustainable forest management (SFM) (Stevenson, 2005). The sustainable forest management paradigm can be defined as management to "*maintain and enhance the long-term health of forest ecosystems, while providing ecological, economic, social, and cultural opportunities for the benefit of present and future generations*" (The State of Canada's Forests, NRC/CIF, 2001/2002). To achieve SFM, the Canadian Council of Forest Ministers (CCFM) developed a system which addressed SFM values through the development of criteria and indicators to serve as management benchmarks for assessing the sustainable use of forests. In Alberta, CCFM criteria are addressed through the Alberta Forest Management Planning Standard (Annex 4 - performance standards). These planning standards require that protection of watersheds and riparian areas must be addressed in the forest management planning process. However, there is currently no scientifically based provincial framework, other than those set forth by the CCFM that address specific concerns quantifying impacts of forest disturbance on hydrology (water quantity and quality). The present difficulty in defining sound management policies and methodologies for monitoring the impacts from forestry operations is evidence that SFM of water resources and the development of hydrologic criteria and indicators remains to be adequately addressed.

One of the difficulties of incorporating hydrologic criteria and indicators into management frameworks is that hydrologic processes are highly variable across landscapes, climates, elevations, forest types and spatial scales (Buttle *et al.*, 2000). Alberta has a broad range of elevations, topographic and climatic conditions; and therefore, exhibits highly variable hydrologic behaviour at a provincial scale. This spatial variability creates difficulties for determining which hydrologic criteria are important and how these hydrologic parameters may be applied across the large forested areas of the province. Complete information describing Alberta's hydrologic characteristics are currently limiting the development of scientifically based criteria and indicators for sustainability of water resources in forest management. A starting point to explore and describe the spatial variability in provincial hydrologic behaviour is to group watersheds into homogeneous regions characterized by having similar hydrologic behaviour. The classification of hydrologic systems is well established in literature and many different approaches to classification have been tested; however, there is no explicit consensus on how catchments should be organized into similar groups exhibiting common hydrologic behaviour (Beven, 2000; Wagener *et al.*, 2007). Among classification approaches, there are two approaches that have been most often used for hydrologic classification. The first is a landscape based classification approach that assumes the physical features of catchments are representative of hydrologic similarity. The second is a streamflow based approach, where hydrometric indices are calculated (e.g. mean monthly streamflows; Haines *et al.*, 1988) and grouped according to their similarity. Both of these approaches incorporate multiple variables for grouping watershed into homogeneous regions with objectives to explore which landscape or hydrologic characteristics or combinations of characteristics are influencing hydrologic behaviour the greatest. Defining suitable hydrologic indices that contribute to better understanding of regional differences in hydrologic behaviour across Alberta remains one of the major barriers to understand the impacts of forest disturbance on hydrologic processes within a catchment.

1.2 Research goals

The objectives of this research were to (1) classify Alberta's forested landbase into homogeneous hydrologic regions using long term streamflow records, (2) examine co-variance of these hydrologic regions with physiographic characteristics of study catchments thought to be influencing hydrologic behaviour, and (3) determine the historic range of natural variation of a number of hydrologic parameters across Alberta's green zone. The overarching goals of these three objectives was the development of a hydrologic risk assessment framework to enable a more accurate evaluation of the projected impacts of forest disturbance on streamflows and other hydrologic indicators for the forested landbase of Alberta. These objectives are intended to support the development and evaluation of forest management plans (FMP) across Alberta.

1.3 Research Objectives

Chapter Two presents and tests an approach to hydrologic classification based strictly on the shape factor of hydrographs using mean annual streamflow records to group catchments into regions with similar streamflow regimes. Related objectives were to (1) describe the hierarchy or order of spatial segregation of hydrologic regions to explore the spatial variability of hydrologic behaviour in the province, and (2) determine if hydrograph shape factor simultaneously captured regional differences in a broad set of independently calculated hydrologic variables representative of the overall streamflow regime (magnitude, timing, frequency and duration of streamflows) which would support the use of this approach as a powerful and parsimonious approach to hydrologic classification.

In chapter Three, I examined differences in the physical attributes of catchments between hydrologic regions developed in chapter two and relate physiographic characteristics to differences in hydrologic behaviour among these regions. Specific objectives were to (1) characterize the regional variation in catchment physiography and land cover classes between hydrologic regions using digital elevation models (DEM) and remotely sensed land cover data, (2) examine the covariance between the physiographic and hydrometric characteristics across hydrologic regions, and (3) use these results to examine how catchment physiography and land cover may be influencing regional differences in streamflow regimes at a landscape scale.

In Chapter Four, I developed a Risk Assessment Framework to explore how differences in the regional hydrology across Alberta might produce differential effects on streamflow regimes as a result of forest harvesting. The risk assessment framework was developed by (1) identifying a sub-set of hydrologic variables that were sensitive to, and that co-varied with gradients in mean annual streamflow to explore the presence of potential hydrologic thresholds and to create linkages to current forest management planning tools; however, if hydrologic thresholds were not evident, the natural range of variation (NRV) would subsequently be explored and defined for selected hydrologic variables. (2) Examining the regional differences in hydrologic thresholds (if present) or the NRV of selected hydrologic variables to explore if regionally specific hydrologic criteria and indicators should be developed. (4) Incorporate the above relationships into an integrated forest planning risk assessment framework, demonstrated using a case study, to explore potential hydrologic thresholds identifying how the projected impacts of different forest management scenarios relate to defined thresholds of the NRV among selected hydrologic variables across hydrologic regions. The findings of this study will provide guidance for evaluating hydrologic change as a result of planned forest management activities by developing linkages to currently used forest planning and watershed assessment tools (models).

1.4 References

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Chapter 2: Hydrologic Classification of Alberta's Forested Regions

2.1 Introduction

Efforts to classify the hydrology of landscapes have historically focused on categorizing the variability of hydrologic behaviour into similar groups based on landscape characteristics such as climate, geology, soils, vegetation, or topography (Sivapalan, 2003). These physical landscape based approaches to classification are often used to better understand the dominant controls of catchment structure and climate on streamflow response for the purpose of grouping landscapes into regions of similar hydrologic behaviour (Wagener, 2007). While climate and physiography are important higher order hydrologic controls, the complex interaction of climate and physiography can produce a wide range of hydrologic responses making it difficult to establish a hierarchy of controls for use in a classification framework (Buttle, 2006; McDonnell and Woods, 2004). Where the purpose of classification is to provide insights into the processes governing hydrologic behaviour of landscapes, a major challenge is selecting the hierarchy of controlling factors hypothesized to be influencing hydrologic response. However, this hierarchy of dominant controlling factors is typically assumed *a priori*, which potentially constrains the classification framework by restricting opportunities to generate inferences surrounding interaction of hydrologic controls. Furthermore, this constrains inferences regarding controls on hydrologic behaviour to those governed by the selected hierarchy which can potentially mask patterns of regional hydrologic behaviour. These landscape based approaches frequently rely on numerous process based parameters to regionalize hydrologic trends and similarities often leading to weak relationships with actual streamflow behaviour within regions (Yadav *et al.*, 2007).

The landscape based approach has remained one of the primary methods of classification in hydrologic science for many decades; however, more recent approaches are focusing on classifying homogeneous regions based on streamflow characteristics and subsequently assessing similarities in landscape characteristics. This alternative approach has the distinct advantage of using streamflow as the primary data source in classifying homogeneous regions, which is most often the variable of interest in a water resource management setting. A streamflow based classification approach involves characterizing the variability of streamflows by using representative measures of the streamflow regime (Poff *et al.*, 1997). The streamflow regime is defined by a broad suite of streamflow characteristics including streamflow magnitudes (e.g. high, average and low flows); the temporal distribution of high, average and low flows (e.g. when they occur throughout the year); the degree of flashiness or stability in streamflows (e.g. the predictability of flows); the frequency (e.g. number of occurrences) of flood and drought events; and the duration (e.g. the length of time) of high, average and low flows (Poff *et al.*, 1997). This approach has the distinct advantage of producing a classification system based on the primary response of interest (e.g. streamflow) that also reflects and captures the effects of all higher order controls influencing streamflow behaviour. Hydrologic classifications based on streamflow regimes have the potential to provide insights on how land and water resources management decisions may impact hydro-ecological connections that may influence hydrological and ecological change.

One of the difficulties with using a classification approach based on hydrologic characteristics is the selection of appropriate streamflow variables; over 200 hydrologic variables have been used to describe flow regimes (Olden and Poff, 2003). Although many of the hydrologic variables explored by Olden and Poff (2003) were strongly redundant which permitted selection of a reduced (non-redundant) set of variables, this approach still requires selecting streamflow variables that are of primary value in classifying hydrologic variability or that are of primary interest to water resources management. One approach is to explore a broad range of variables, examine them for redundancy and select those that are most representative of the study area, thus providing the specific information needed to meet scientific or management objectives. The other solution to this problem is selecting variables that integrate or capture the entire range of streamflow characteristics needed to meet the scientific or management objectives of the classification. Conceptually, these approaches can be simplified further in the idea that the streamflow regime is captured by the surface water hydrograph; as it is reflective of information directly related to the temporal variability of a streamflow regime within a catchment. By comparing surface water hydrographs from different catchments, differences and similarities in the timing, magnitudes, and frequencies of high, average and low flows as well as the durations of flow spells (floods or droughts) can be explored. The methodology of this technique involves separating the magnitude component from the temporal component of the hydrograph by standardizing streamflow observations (typically monthly averages) resulting in a measure describing the "shape factor" of the hydrograph (Harris *et al.*, 2000).

The general concept of using hydrograph shape factor as an integrated variable for classification has been successfully used to classify daily streamflows into climatic regions (Hanna *et al.*, 2000) and assessment of streamflow response to patterns of climatic variation (Harris *et al.*, 2000) in the United Kingdom. One particular classification approach focuses on the shape factor of the hydrograph to provide insights into the variation of flow regimes at different spatial and temporal scales (Bower *et al.*, 2004). Hydrograph shape factor has been used for hydrologic classification to examine relationships between annual variation in streamflows with abundance and diversity of macroinvertebrate communities in the United Kingdom (Wood *et al.*, 2001). More recently, Monk *et al.* (2006) used hydrograph shape factor to classify streams into regions with similar hydrograph shapes and subsequently related regional variation in streamflows to macroinvertebrate community structure to reveal unique patterns of species composition and diversity between regions with different streamflow regimes. In these examples, classification using hydrograph shape factor captured both the temporal and spatial variation in streamflow regimes and additionally highlighted patterns of physiographic and hydro-climatic controls across landscapes. Snelder *et al.* (2009) found strong relationships between regions that were classified using multiple hydrologic variables and physical basin characteristics with mean annual regional hydrographs; supporting that a simplified classification approach based on hydrograph shape factor may be sufficient to capture the variation in streamflow regimes across larger spatial scales while still providing opportunities to investigate the influence and interaction of higher order controls on hydrology. However, while these recent approaches may suggest the use of hydrograph shape factor to serve as a simplified and robust variable for hydrologic classification, the extent to which this simplified variable co-varies, captures, or describes variation in a wide range of streamflow characteristics among differing hydrologic regions has not been explored. If hydrograph shape factor could be shown to adequately capture the differences or similarities among regions for a potentially wide range of hydrologic behaviour, this would establish the use of hydrograph shape factor as a parsimonious or "master" variable that would meaningfully advance its application to regional hydrologic classification based on observed streamflow behaviour of similar hydrologic regions.

The overall objective of this study was to present and test an approach to hydrologic classification based strictly on the shape factor of hydrographs using standardized mean annual streamflow records to group catchments distributed across the forested area of Alberta, Canada into regions with similar streamflow regimes. A specific objective of this study was to describe the hierarchy or order of spatial segregation of hydrologic regions in Alberta to explore the spatial variability of hydrologic behaviour in the province. A related objective was to explore if classification based on hydrograph shape factor simultaneously captured regional differences in a broad set of independently calculated hydrologic variables representative of the overall streamflow regime (magnitude, timing, frequency and duration of streamflows) which would support the use of this approach as a powerful and parsimonious approach to hydrologic classification.

2.2 Methods

2.2.1 Study region and data assembly

This study was focused on hydrologic classification of forested regions within the province of Alberta (Figure 2-1). This region is primarily managed for timber, non-renewable resource extraction (mining, petrochemicals), and public wildlands. The forested region covers 352,477 km^2 (53 percent) of the province and is held mostly under public ownership (crown land). This region is commonly referred to as the 'Green Zone' of the province. Alternately, the 'White Zone' is mostly privately owned land primarily managed for agriculture (livestock production, grazing or croplands) and encompasses 256,194 km^2 (39 percent) of the province. The remaining eight percent of the province consists of federal lands (Government of Canada) designated as national parks, which for the most part are composed of forested and mountainous lands.

2.2.1.1 Climate and physiography

Alberta's forested regions have variable physiography, climate and streamflows that correspond to a gradient of decreasing elevation from west to east. In western Alberta, the northern Rocky Mountains contain the highest elevations ranging from 825 meters to over 3600 meters in alpine areas. This area is characterized by steep slopes of bedrock, colluvium and residual materials overlain by thin poorly developed soils. Moving east at lower elevations (650 to 1750 meters) the upper and lower foothills are characterized by broad valleys with rolling topography, overlain by deeper glacial tills with fluvial deposits and characterized by more developed soils. At lower elevations ranging from 200 to 1525 meters the Boreal forest and parkland areas form the largest portion of the province (Downing and Pettapiece, 2006). The topography of the Boreal forest and parkland area varies from hummocky uplands to undulating and level plains and is characterized by deep glacial tills, lacustrine and silty and sandy fluvial materials. Precipitation generally parallels topographic gradients with the Rocky Mountain and the Foothills areas receiving higher mean annual precipitation ranging from 588 mm to 989 mm, and 588 mm to 632 mm respectively. The lower elevation Boreal forest and parklands receive less precipitation (242 mm to 535 mm), two thirds of which falls in the summer months (Downing and Pettapiece, 2006). Streamflow follows similar patterns with the highest water production and runoff ratios originating in the Rocky Mountains and foothills with lower amounts of runoff in the Boreal forest and parklands to the east and north.

2.2.1.2 Selection of historic streamflow records

The regions selected for this study included the green zone of Alberta, wildland national parks adjacent to and within the green zone, a smaller sub-region of the white zone located immediately adjacent (within 80 km) to the green zone, and lastly a region within 100km of the entire province. The regions outside of the green zone were included because a) they contained significant forested areas, b) streamflow data collected by many of the government operated hydrometric gauging stations reflect streamflows that are mostly generated from within the forested green zone region of the province and c) some streamflow generated within the forested region was gauged outside the province. The primary data for this study consisted of historic streamflow records collected by Water Survey of Canada (WSC) as part of the Environment Canada national hydrometric monitoring program. A preliminary list of potentially suitable hydrometric gauging stations operated by WSC was abstracted from Environment Canada’s hydrometric online database (Environment Canada, 2003) This initial list consisted of 1059 hydrometric gauging stations distributed throughout the study region (Figure 2-1).

This preliminary list was reduced by selecting stations meeting a number of criteria to select a final list of suitable stations with historic data for this study. These criteria and their rationale were as follows:

1) Record length: Minimum total record length of ten years. This was selected to ensure mean annual hydrographs used for classification were adequately representative of the inter-annual climatic variation produced by wet or dry years in the hydrometric record.
2) Data record continuity: Stations with continuous daily records (full annual daily records) or seasonally operated stations (March through October daily records) were selected for analysis to exclude those stations with intermittent operation.
3) Natural flowing streams: All study watersheds were selected to be naturally flowing systems to exclude those with engineered diversions or impoundments (regulated flows) that would not be representative of a natural hydrologic system.
4) Watershed area: The maximum area of study watersheds was limited to 2000 km^2. This was primarily to limit the study population to smaller watersheds and minimize the scale dependence of the results.

Application of these criteria reduced the number of potential hydrometric gauging stations from 1059 (Figure 2-1) to 215 which were reasonably well distributed across the study area (Figure 2-2), (Appendix 2-1). Fifty-eight percent of all stations were located in the 80 km buffer to the forested area (the white zone). The forested area (the green zone) contained an additional thirty-four percent and the remaining eight percent of study catchments were located in national parks. Study catchments areas ranged from 1 km^2 to 1960 km^2 with a mean area of 475 km^2 and median area of 278 km^2 (Figure 2-3). Seventy-two percent of selected gauging stations had seasonal data records with the remaining twenty-eight percent having continuous hydrometric data records. Data records varied from the selected minimum length of 10 years to a maximum record length of 83 years (Figure 2-4). Average record length was 39 years with a median record length of 32 years. Of all the hydrometric gauging stations, only forty-four percent were operational and actively collecting data at the time of database assembly. The remaining fifty-six percent were discontinued, but had been operational at some point since 1908 (Figure 2-5). The selection criteria (listed above) resulted in a total of 6785 station record years of hydrometric data from the 215 hydrometric gauging stations. Eighty three percent of hydrometric station data records ranged from 1971 to 2007, the other 17 percent of the hydrometric station records were collected between 1908 and 1970. The period of record from 1971 to 2007 reflects 30 years of streamflow observations across the forested region of the province and comprises the majority of the available hydrometric data; thus, this length of time (30+ years) is considered as the temporal period that conclusions can be draw from and is considered to be the long term average hydrologic condition during the latter half of the 20th century for Alberta.

2.2.1.3 Preliminary processing of streamflow data records

For each of the 215 hydrometric stations, mean daily volumetric discharges (m^3/s) were converted to area-depth (mm/day) using the effective drainage area reported for each station by WSC. Because annual water yield (mm/yr) was one of the streamflow variables needed in subsequent analysis, incomplete winter flow records of WSC stations with seasonal operation needed to be estimated using gap filling techniques to enable calculation annual values. For stations with seasonal operation, a baseflow recession constant was applied to estimate the recession limb of the annual hydrograph for every year in the flow record of each station (Figure 2-6).

Equation 2-1 $$Q_t = Q_o (K_b)^t e^{\varepsilon t}$$

Equation 2-1 (Vogel and Kroll, 1996) is derived by treating the watershed as a linear reservoir where Q_o is equal to the initial baseflow value, Q_t is baseflow after t days, K_b is the baseflow recession constant and $e^{\varepsilon t}$ are independent normally distributed errors with a constant variance and mean of zero. Baseflow recession constants were computed from Equation 2-1 for all years where a clear base flow recession was present or by using complete annual hydrographs from nearby stations that had continuous data and were generally similar in area for the watershed with seasonal records. This technique has been used to enable gap filling of the receding limb of annual hydrographs during winter months where data is often absent (Vogel and Kroll, 1996). In this study, gap filling overwinter baseflow recession of annual hydrographs was necessary to calculate hydrograph shape variables to be used in both regional hydrologic classification and calculation of mean annual water yield for each station.

2.2.2 Statistical hydrologic analysis

2.2.2.1 Hydrologic classification using cluster analysis

Regional hydrologic classification using hydrograph shape factor involved a two-step process. A multivariate shape factor that described average annual variation in streamflow was calculated for each station. Cluster analysis was then used to classify the population of 215 WSC stations into homogeneous groups with distinct annual hydrograph shape factors.

2.2.2.1.2 Shape factor

Hydrograph shape factor for each station was derived from each hydrometric records mean annual hydrograph. The mean annual hydrograph (time series data) served as the initial basis in forming the multivariate dataset for each station. Mean annual hydrographs at a daily time-step (mm/day) were averaged across station years by summing mean daily streamflows (mm/day) over a 3 week period (21 days) resulting in an abstracted mean annual hydrograph represented by 18 time steps of the mean 21-day total streamflow (mm/21 days). Eighteen time steps were selected as a balance between the need to provide adequate temporal resolution for the mean annual hydrographs (e.g. retain the shape of the annual hydrograph) without an excessive amount of temporal variability or noise in the data (e.g. signal to noise ratio). The series of 18 hydrograph time steps were then standardized using z-scores (mean = 0, standard deviation = 1). Standardization served to effectively remove differences in flow magnitude among stations but also preserved the standardized hydrograph shape factor unique to every watershed. Standardization is a common technique for comparing data of different units or data sets that differ by orders of magnitude (Mohan and Arumugam, 1996). The resulting 18 variables served as the multivariate time series dataset representing the hydrograph shape factor, for regional hydrologic classification using cluster analysis techniques.

2.2.2.1.2 Cluster analysis

Cluster analysis was selected as the primary technique for classifying this type of multivariate dataset. The primary objective of cluster analysis is to classify observations into homogeneous groups so that there is a high degree of association within groups and a low degree of association between groups (Anderberg, 1973). A distinct advantage of cluster analysis is that no *a priori* assumptions of how observations should be organized are needed, allowing unconstrained identification of groups based exclusively on similarity of observations using various distance measures in multivariate space (Dillon and Goldstein, 1984). Agglomerative, hierarchical cluster analysis using the between group, average linking method (SPSS version 16.0, SPSS Inc. Chicago, IL, USA) was used to group hydrometric records that had similar hydrograph shape factors based on the 18 standardized time steps of the mean annual hydrograph for each station. The average linkage method has been shown to be a suitable technique for cluster based classifications of climatic datasets over Ward's or the Centroid methods as it maximizes inter-cluster and minimizes intra-cluster variances (Kalkstein, 1987). Although the 18 shape variables were standardized (mean = 0, S.D. = 1) across the 215 stations to create shape factor variables independent of streamflow magnitudes, the absolute magnitude of standardized streamflows (represented by dimensionless z-scores) ranged from -1.77 to 3.89. To further reduce the influence of the magnitudes of standardized values during cluster analysis the Euclidean distance measure was used as it does not place greater emphasis on objects that are further apart in multivariate space; unlike the squared Euclidian distance measure which would disproportionately increase the influence of larger z-score values in determining cluster membership (Anderberg, 1973; Dillon and Goldstein, 1984).

Because cluster analysis is an exploratory data analysis technique, there are no specific tests to determine optimal number of groups to retain for any particular dataset. Thus, 20 separate cluster analyses were performed on the study dataset in which the number of groups (clusters) was sequentially increased from 2 to 22 groups with the expectation that the most meaningful classification solution (e.g. number of homogeneous groups) would be bracketed within this range of solutions (2 through 22 clusters). A more quantitative approach to identifying a clustering solution was based on evaluating sequential changes in the proportion of total variance explained at each step in the clustering analysis from 2-22 groups (Halkidi, 2002). Four different statistical parameters can be used to explore this change in total variance explained at each step in the cluster analysis. (1) The R-squared (RSQ) is the sums of squares (*SS*) between different clusters relative to the total sums of squares, defined by:

Equation 2-2 $$\frac{SS_{betweengroups}}{SS_{total}}$$

Where; $SS_{total} = SS_{betweengro\ ups} + SS_{within}$, SS_{within} is the sums of squares of the newly formed cluster and therefore $SS_{between\,groups} = SS_{total} - SS_{within\,groups}$. This parameter indicates the degree that clusters are different from one another at each successive step of the clustering process (Frossyniotis *et al.*, 2005). (2) The semi-partial R-squared (SPRSQ) is the ratio between the difference of K clusters and the K+1 clusters *SS* divided by the *SS* for the entire data set calculated by:

Equation 2-3 $$SPRSQ = \frac{SS_{wk} - SS_{w_{k+1}}}{SS_t}$$

Where; SS_{wk} is equal to the *SS* within the K^{th} cluster and the SS_{wk+1} equals the *SS* within $K^{th} + 1$ cluster of the next largest grouping. This index measures the loss of homogeneity at each successive merger of two clusters, with low SPRSQ values indicating a merger of two homogeneous clusters and increasing values indicating a merger of more heterogeneous clusters (Halkidi, 2002). The calculated RSQ and SPRSQ values for each clustering solution were plotted against the 20 sequential steps of 2-22 cluster groupings to identify a numerically optimal solution explaining the most of the variance with the fewest number of groups (a quasi-optimal solution). (3) Cluster output from the largest number of potential groups (22 groups) was compared by plotting dendrogram distances and (4) agglomeration schedules of proximity coefficients generated by the model at each clustering stage. For the validation methods listed above, the optimal clustering solutions are often indicated at the “knee” or inflection point of the curves (Halkidi, 2002; Frossyniotis *et al.*, 2005; Isik and Vijay, 2008).

Lastly, the qualitative examination of the spatial distribution of groupings across the study area at different clustering stages reflected the spatial variability of hydrologic behaviour across the study region. Visual inspection of the cluster groupings at sequential steps in the clustering procedure revealed spatial patterns of decreasing variance with successively greater numbers of groups. In other words, this procedure identified the relative strength and spatial location of the variability in hydrologic behaviour across the study region. This allowed for preliminary exploration of how the spatial location of the groups co-varied with landscape features associated with basic hydrologic controls (e.g. climate, elevation).

2.2.2.1.3 Canonical discriminant analysis

Canonical discriminant analysis using the SAS statistical package (Version 9.1, SAS Institute Inc., Carey, North Carolina) was applied to explore which time periods (18 flow periods) of the standardized hydrograph shape factors contributed most to separation of hydrologic regions for the final cluster analysis solution. Canonical discriminant analysis is a multivariate dimension reduction technique that indentifies linear combinations of variables that provide the greatest degree of separation between defined groups (SAS, 2008). The resulting canonical coefficients can be examined to determine linear combinations of variables having the greatest multiple correlations between groups, with each successive canonical correlation function being uncorrelated with the first. The scored canonical variables can then be plotted to help interpret which combinations of variables are contributing most to group differences and to help visualize the degree of separation between groups. As this statistical method is linear, data sets were checked for (1) assumptions of multivariate normality by examining frequency distributions, (2) homogeneity of variance/covariance using the multivariate Box M test, and (3) examining correlations between the means and the variances across groups. Although this statistical method is robust to minor deviations in normality and homogeneity of variance/covariance, data sets were first transformed using the natural log and then standardized using Z-scores to assure accuracy of results and ensure validity of statistical significance.

2.2.2.2 Regional analysis of hydrologic variables

The hydrologic classification procedure outlined above was based solely on the standardized shape factor of mean annual hydrographs which effectively only reflects information on the mean temporal pattern of streamflows. No other attributes of streamflow (e.g. magnitude; peak flows, low flows, etc.) were contained in the dataset. The differences in a much broader set of hydrologic variables describing streamflow variation among the regions classified above were explored to examine if hydrologic classification based solely on hydrograph shape factor was truly useful in distinguishing regions differing in hydrologic behaviour. A classification system based on a simple set of hydrologic variables, that also distinguished among regions differing in a much broader set of variables could be considered robust or parsimonious.

To determine if the final spatial classification reflected variation in streamflow parameters not explicitly considered in data used for classification; additional hydrologic variables thought to be important to water resource managers were calculated. These hydrologic variables also served as a finer filter to asses the utility and representativeness of the coarser classification approach of hydrograph shape for defining hydrologic regions. Hydrologic variables were selected based on their potential sensitivity to change from natural or anthropogenic disturbance and from research guiding the selection of hydro-ecological indices (Richter *et al.*, 1996; Olden and Poff, 2003). Thirty six streamflow variables (Table 2-1) were selected to represent the overall hydrologic regime organized by the following streamflow categories:

1) Magnitude: Variables in this category represented annual low, average and high flow conditions of differing temporal scales ranging from 1, 3, 7 and 30 day to average annual streamflows. Regional flow duration curves (FDC) were also evaluated in this category and contained 13 variables associated with the magnitudes of specific flow exceedance probabilities for each hydrologic region.
2) Timing: Variables in this category represented the annual dates of occurrence for specific flow conditions such as the dates of minimum and maximum streamflows, half flow dates, and dates of seasonal (summer) low flows.
3) Frequency: Variables in this category represented the annual number of discrete flow conditions (number of high and low flows) as well as the slope and intercept of regional flood frequency relationships.
4) Duration: Variables related to streamflow duration described the length of time (days) that a specific flow condition (high and low flows) persisted in any given year.

The 36 flow variables were calculated for every year in the flow record for each of the 215 stations and then averaged across station years, to produce an overall mean value for each study watershed.

2.2.2.2.1 Analysis of variance

Analysis of variance (ANOVA) and subsequent post-hoc tests were used to determine if each hydrologic variable differed between groups identified by cluster analysis and to identify which of the 36 hydrologic variables differed among regions classified with hydrograph shape factor. Separate one-way ANOVAs were conducted on each of the 36 variables to determine if hydrologic variables differed between cluster groupings for the final classification solution. For variables where significant differences existed among groups, post-hoc multiple range tests were used to identify significant differences among specific regions (α=0.05). All variables were assessed for normality using P-P, Q-Q plots and the Shaprio-Wilk test. Levene's statistic (Zarr, 1999) and plotting of the standard deviations and variances against the means, along with plots of observed and predicted residuals were examined for homogeneity of variances. Where data was not normally distributed or violations in homogeneity existed, variables were transformed using the natural logarithm (Ln). Most hydrologic variables related to magnitudes and durations of flows were skewed and subsequently transformed to meet statistical assumptions of linearity. Variables related to the timing (half flow date, day of max Q, day of seasonal low Q,) and frequency (number of high flows, slope of the regional FF regression line) of streamflows approximated a normal distribution and had equal variances. While ANOVA is robust to minor deviations in normality and inequality of homogeneity in variance with the condition of equal group sizes; this was not the case with our hydrologic regions thus traditional ANOVA results could have resulted in misleading F-statistics. To increase confidence in analyzing regions with unequal group sizes, two additional statistical tests were used (1) the Welch statistic and (2) the Brown-Forsythe statistic. Both of the above statistical tests are valid for ANOVA with unequal group sizes (Zar, 1999). For variables found to be significant from ANOVA, 'post hoc' tests were used to determine specific differences between regions. Tukey's HSD test is preferred over other post-hoc tests as it is more conservative when group sizes are unequal; however, Tamhane's T2 test was used for variables where the assumption of equal variances did not hold and is also suitable for comparisons between groups with unequal sizes (Tamhane, 1979; Zar, 1999). For multivariate flow variables such as flow duration curves (FDCs), Multivariate Analysis of Variance (MANOVA) was used to test for differences in the overall FDC among classified hydrologic regions.

2.2.2.2.2 Canonical discriminant analysis

Because many of these 36 flow variables were likely strongly correlated with each other (Olden and Poff, 2003; Clausen and Biggs, 2000), canonical discriminant analysis was used to determine which hydrologic variables or groups of variables were most different among hydrologic regions classified using hydrograph shape factor. Canonical discriminant analysis is a dimension reduction technique closely related to principal components analysis (PCA) that is well suited to this question as it identifies linear combinations of variables that provide the greatest degree of separation between previously defined groups (SAS, 2008). Because canonical discriminant analysis also identifies which groups of variables are highly correlated with one another, this is a useful technique to identify groups of redundant (highly correlated) streamflow variables. Canonical discriminant analysis was performed on the averaged values for all station years of the entire set of 36 hydrologic variables from each of the 215 WSC stations. Again, as this statistical method is linear, data sets were checked for assumptions of multivariate normality and homogeneity of variance/covariance and transformed using the natural log if necessary.

2.3 Results

2.3.1 Hydrologic classification

2.3.1.1 Cluster analysis based on hydrograph shape factor

Cluster analysis using the hydrograph shape factor from each of the 215 study watersheds was performed in 20 sequential steps to classify the population of stations into 2-22 unique clusters (homogeneous groups). While the first step in cluster analysis separated only one small group of 2 watersheds in the white zone from the rest of the 215 stations, which were considered as outliers, step 2 created two major groups distinguishing stations in the green zone from the white zone (Table 2-2). Step 3 further sub-divided the white zone into 3 groups with no additional divisions of stations in the forested region. In steps 4, 6, and 7 stations in the green zone were further sub-divided into 3 additional groups reflecting high elevation Rocky Mountain watersheds (step 4), a small group of 2 stations in the extreme south (step 6), and 2 additional groups sub-dividing the balance of the forested stations into upper and lower montane and Boreal regions (step 7). No further clusters from the forested region were produced until step 13, when the upper montane group (above) was separated into a northern and southern group (Table 2-2). The white zone stations were sequentially separated into 5 groups in steps 2, 5, 9, 8, 11, and 12 (Table 2-2)

Because cluster analysis does not identify an optimal number of clusters, a semi-quantitative approach based on the changes in RSQ and SPRSQ values at each step in the cluster analysis procedure along with plots of the clustering agglomeration schedule and dendrogram distances were used to identify a quasi-optimal solution that minimized regional differences with the fewest number of groups. Both the RSQ increased and the SPRSQ decreased rapidly as cluster analysis was specified to output greater numbers of groups with an approximate inflection point in both relationships evident between 5-7 groups. An approximate horizontal asymptote in both these relationships appeared evident at the 8 group cluster output of the procedure (Figure 2-7a and b). The agglomeration schedule plot of proximity coefficients showed a positive trend in Euclidean distance as groups were joined; with smaller proximity coefficients indicating shorter distances between groups (greater similarity) and larger coefficients indicating groups were becoming less similar. A distinct change in slope occurred between the 205th and 210th stages of clustering; indicating a potential solution between 10 and 5 groups (Figure 2-7c). Conversely, the relationship of dendrogram distances at each stage in the cluster analysis procedure did not clearly identify a distinct inflection point that might have suggested an optimal solution (Figure 2-7d). Because there was an approximate correspondence in the asymptotes or inflection points of the RSQ, SPRSQ, and agglomeration schedule relationships, the cluster analysis solution with 8 groups (step 7) appeared to represent a solution that described the greatest proportion of total variance in the hydrograph shape factors for the 215 stations with the minimum number of groups. This quasi-optimal solution of 8 groups contained two groups that only included two stations each. These two groups were considered as outliers and omitted from subsequent analysis because; (1) they did not provide sufficient degrees of freedom (n - 1=1) for further analysis, (2) both groups were outside of the specific area of interest (forested land), and (3) additional re-analysis excluding these 2 groups did not change the final cluster results. After removal of these 4 stations (2 small groups), the remaining 211 stations were distributed among six major groups; three of which were located in the green zone and three in the white zone region adjacent to the green zone.

2.3.1.2 Canonical discriminate analysis of shape factor variables

Canonical discriminate analysis was used to determine which temporal periods of the hydrograph shape factors (standardized annual hydrographs consisting of 18 aggregate flow periods) influenced group separation during cluster analysis the most. The overall model in the cluster solution was highly significant ($p<0.001$) with the first four canonical structures explaining 98.9 percent of the variance in the annual hydrograph shape factor dataset for the 215 WSC stations (Table 2-3). The first canonical structure accounted for 69.1 percent of total variance explained with the 2nd, 3rd, and 4th structures explaining an additional 19.4, 7.5, and 2.9 percent of additional explained variance, respectively. Periods 8 (May/June) and 5 (March/April) were negatively correlated among stations and collectively governed the classification of cluster groups in the first structure, while period 6 (early April) and period 3 (late February) had the greatest influence in the second canonical structure (Table 2-3). These first two structures accounted for 88.5 percent of the explained variance in hydrograph shape factors for the 211 stations and resulted in strong separation of groups in multivariate space (Figure 2-8). Regions within the green zone of the province (6, 1, and 5) had the highest loadings along the first dimension (dominated by shape factors for periods 8 and 5, above) and also reflected larger standardized flow magnitudes than other regions. This axis also accounted for the separation of groups in the green zone from groups within the white zone of the province. Conversely, while visual discrimination along the second axis was not as clear as the first, this axis (dominated by periods 6 and 3, above) did discriminate among groups within each of the green zone and white zone groupings. Collectively, these results indicate that the 4 temporal periods spanning March through June which relate to the onset of spring snowmelt and the peak of the annual hydrograph were the most influential in differentiating hydrographs between regions.

2.3.1.3 Spatial attributes of clusters and description of hydrologic regions

The watersheds (and WSC stations) in each group appeared as geographically distinct regions separated in a consistent spatial pattern with well defined boundaries relative to each other (Figure 2-9). Only 3 out of 211 stations appeared geographically separated from their respective groupings.

At the western-most edge of the eastern slopes of the Rocky Mountains, region 6 consisted of nine watersheds located within Jasper and Banff national parks. Region 1 contained 72 watersheds distributed along a north/south gradient at a slightly lower elevation range and in the same general area as region 6 (although one catchment in this group was located in the northern part of the province). Watersheds in this region were either entirely inside or adjacent to the green zone of the province. A total of 62 watersheds formed region 5 which was distributed at lower elevations further eastward across the province's lower east slopes and extending north-east into the Boreal forest. With the exception of four catchments, located within the 80km buffer surrounding the green zone, all watersheds in this region were within or intersected the forested landbase. Watersheds in region 8 were distributed north east of the Rocky Mountains. These 39 watersheds were distributed directly alongside the 80km buffer to the green zone and often intersected the green zone / white zone boundary. Region 7 had 23 watersheds which were also adjacent to the outer edge of the 80km buffer from the green zone, most of which were located in the white zone. Region 7 and 8 showed very similar geographic distributions, although region 7 was consistently further from the green zone boundary than region 8. Lastly, region 4 contained six watersheds scattered within the central and southern part of Alberta. All catchments in region 4 were located outside of the forested land base with the exception of one that crossed into the green zone.

The standardized mean annual streamflows for all WSC stations in these 6 regions were converted back into their original scale (mm/21 day period) to explore the distribution of hydrograph shapes within each group. This highlighted the remarkable efficacy of the clustering procedure at distinguishing and grouping unique regions differing by annual hydrograph shapes (Figure 2-10). All annual hydrographs were characterized by low overwinter baseflows with steeply rising annual peaks coincident with the timing of the spring snowmelt freshet, followed by a clear recession limb from late summer into the fall periods. Annual hydrographs from the 6 regions differed strongly in the timing of the onset and peak of the snowmelt freshet, and while some regions displayed a single snowmelt freshet peak (region 1 and 6), others were characterized by multiple peaks (regions 5, 8, 7 and 4). While a wide range of flow magnitudes were evident within each group, all annual hydrographs shared a characteristically unique shape relative to the other groups. Furthermore, despite the range of flows evident within each group, the 6 regions formed a spatial gradient in streamflow magnitudes. Mean annual hydrographs of watersheds in region 6 were characterized by a single large peak occurring in July to August (periods 10 to 12). This region had the greatest magnitudes of streamflows ranging from 100-500 mm for each 21 day period during the peak of the hydrograph, followed by strongly defined receding limbs. Annual hydrographs from watersheds in region 1 were very similar in those of region 6, but the timing of the snowmelt freshet was considerably earlier occurring during May through July (periods 7-11). Peak discharges during the melt freshet were also approximately 50 percent lower than those in region 6. Hydrographs from region 5 were highly variable in magnitude with the timing of the snowmelt freshet peaking earlier (May/June) than those of region 1. Hydrographs in this region also had large secondary peaks 40-60 days after the peak snowmelt freshet with smaller tertiary peaks evident during September (period 13). The magnitudes of peak discharges in this region were also approximately 4-5 times lower than those of region 1. The shapes of annual hydrographs from region 8 showed one large peak earlier than those in region 5 (April/period 6) with smaller (but more evident) secondary and tertiary peaks from September through November. The overall magnitude of flow from this region was approximately 40 percent lower than that of region 5. Hydrographs of region 7 were similar to those of region 8, though the large initial peak occurred in March/April (period 5) with smaller secondary or tertiary peaks similar to region 7 occurring in late summer or fall. The overall magnitudes of streamflows in region 7 were approximately 50 percent lower than those of region 8. Lastly, hydrographs from region 4 showed a hydrograph shape most unique from all other regions. In this region four subdued peaks were evident in late March, June, late September and with the last peak occurring during October / December. Although the hydrographs from all regions showed clear dominance of spring-summer streamflows, these 6 distinct regions formed a monotonic gradient of both increasingly earlier timing of the melt freshet peaks and decreasing flow magnitudes from west to east.

2.3.2 Regional analysis of hydrologic variables

Because the hydrologic classification procedure was based solely on the standardized shape factor of mean annual hydrographs (temporal pattern of streamflows), differences in 36 hydrologic parameters (Table 2-1) describing flow magnitude, timing, frequency, and duration were tested among regions to explore the parsimony of shape factor analysis in representing regions of differing hydrologic behaviour.

2.3.2.1 Analysis of variance of hydrologic variables

Most hydrologic variables differed significantly among the six regions ($\alpha = 0.05$) except for the day of minimum Q, number of low streamflows, duration of low streamflows, and duration of seasonal low streamflows (Table 2-4). Given the significance of ANOVA, post-hoc multiple comparison tests were used to examine specific differences between each region and the remaining 32 hydrologic variables (Table 2-4). Post-hoc tests showed that distinct patterns were evident among hydrologic variables within each flow regime category between the six hydrologic regions. The majority of differences were found among the 3 green zone regions and between the green zone and white zone regions with few differences found among regions in the white zone.

Variables in the streamflow magnitude category (variables 1-11, Table 2-1) followed a regional spatial pattern with the highest streamflows in the Rockies declining in magnitude towards the white zone regions in the east. Mean annual Q and half annual Q (not shown) were highest in region 6 followed by regions 1, 5, 8, 4 and 7 with mean annual streamflows of 935, 311, 126, 51, 39 and 24 mm/year respectively (Figure 2-11). Maximum streamflows (1, 3, 7, and 30 day mean annual maximum streamflows) showed a similar pattern among regions with the largest maximum streamflows in region 6 followed by regions 1, 5, 8, 7, and 4 (Figure 2-12a, b, c, and d). Similarly, minimum annual streamflows (1, 3, 7, and 30 day minimum Q) were greatest in regions 6 (0.08mm), 1 (0.06mm) and 4 (0.02mm) followed by regions 5, 8, and 7 that had minimum streamflows of less than 0.01mm (Figure 2-13a, b, c, and d). Seasonal minimum streamflows were 1.7, 0.43 and 0.11 mm/day across regions 6, 5 and 1 and ranged from 0.5mm/day in region 4 to less than 0.01mm/day in region 7 (Figure 2-14). A consistent pattern was observed in the variability of streamflow magnitudes within green zone regions (6, 1 and 5) which had larger variation then white zone regions (8, 7, and 4). The exception to this pattern was for mean annual minimum streamflows and seasonal minimum streamflows and thus suggesting that regions in the white zone were more variable than regions in the green zone for parameters describing minimum streamflows.

Hydrologic descriptors of streamflow timing (variables 25-28, Table 2-1) followed a similar regional spatial pattern to what was observed with streamflow magnitudes. The day of maximum annual streamflow occurred later in forested regions (Julian day) 6 (190), 5 (167) and 1 (163) and earlier in white zone regions 8 (136), 4 (125) and 7 (114)

(Figure 2-15a). The date of minimum seasonal low streamflows (Figure 2-15b) and date of half annual streamflow (Figure 2-15c) followed the same temporal pattern with regions 6, 5 and 1 having minimum seasonal low streamflows occurring on Julian days of 268, 253, 241 (later) and dates of half annual streamflow occurring on Julian day 202, 174 and 170 (later), respectively. White zone regions had both earlier dates of minimum seasonal low streamflows and dates of half annual streamflows with average dates of minimum seasonal low streamflows occurring on Julian days of 240, 236, 233, and dates of half annual streamflows of 146, 143 and 118 in regions 8, 4, and 7, respectively. The Julian date of minimum streamflow was not significant between hydrologic regions (Table 2-4) (figure not shown).

Variables related to the frequency of streamflows (variables 29, 30, 35 and 36, Table 2-1) can effectively be separated into two groups (1) descriptors of regional flood frequency (FF) where the slopes and intercepts between regional FF regression lines were compared and (2) descriptors of the discrete number of flow events (high, low, and seasonal low flows). The FF slope was steepest and most variable for the forested regions (1, 5 and 6) in descending order respectively, followed by the white zone regions 8 and 7 with region 4 having the lowest FF slope values (Figure 2-16). The FF intercept was highest in region 6, followed by lower intercepts in regions 1, 5, 8, 7, and 4 with patterns of variance following similar trends (Figure 2-17). Region 6 had the most discrete high flow events (approximately 6 per year) followed by regions 5 and 4 (approximately 5 per year) and regions 1, 8 and 7 with annual averages of 4 high flow events per year (Figure 2-18). Seasonal low flow events were more frequent in regions 8, 4, and 7; least common in regions 5 and 1, and were not evident in region 6 (Figure 2-19). The discrete number of low flows was not significantly different ($\alpha = 0.05$) between any of the hydrologic regions (Table 2-4) (figure not shown).

The only significant ($\alpha = 0.05$) variable in the category of streamflow duration (variables 31, 32, and 34, Table 2-1) was the duration of high streamflows. Green zone regions (1, 5, and 6) had high flows of the shortest duration, ranging from 7 to 11 days; followed by regions 7, 4 and 8 with durations ranging from 12 to 18 days (Figure 2-20). The duration of seasonal low streamflows (July to September) and annual low streamflows were not significantly different between regions (Table 2-4) (figures not shown).

To test the significance of regional flow duration curves (FDC) between hydrologic regions MANOVA and subsequent multivariate comparisons between FDC exceedance probability magnitudes and hydrologic regions were evaluated. Regional flow duration curves were highly significant between hydrologic regions (F [13,193] = 0.059; p<0.0001) and showed clear differences in magnitudes. Region 6 had the highest magnitudes for every exceedance probability of the FDC, followed by region 1 and 5. The 3 regions in the white zone (4, 8 and 7) had the lowest FDC magnitudes (Figure 2-21).

2.3.2.2 Canonical discriminant analysis of hydrologic variables

Results from ANOVA indicated most of the 36 hydrologic variables were significantly different among regions, thus canonical discriminant analysis was used to determine which hydrologic variables (or groups of variables) represented the greatest differences among regions. This analysis also served as a method to examine redundancy in the hydrologic variables by identifying highly correlated groups of variables

Analysis of the 36 hydrologic variables by region showed all 5 canonical structures had significantly different class means (α = 0.05), supporting ANOVA results that most hydrologic variables were significantly different among regions (α = 0.05). However, only the first 3 canonical axes had eigenvalues greater than 0.95; which has been used as an approximate threshold for evaluating 'meaningful' canonical structures (Zwick and Velicer, 1984). These 3 canonical structures accounted for more than 92 percent of the overall variance (Table 2-5). The first canonical structure accounted for 70.7 percent of the variance in the model, while the 2nd and 3rd structures accounted for 14.4 percent and 7.7 percent of additional variance explained, respectively. The pooled canonical structures of the first dimension indicated positive correlations (listed in descending order) between minimum seasonal low flows, half flow date, FDC probabilities of 0.4 and 0.5, day of maximum streamflow, FDC exceedance probabilities of 0.3 and 0.6, mean annual streamflow and half annual streamflow (Table 2-5). Thus, this dimension represented flow variables related to both the magnitude and timing of streamflows with watersheds in the green zone (regions 6, 1 and 5) having larger flow magnitudes and later timing of streamflows than watersheds in the white zone region (Figure 2-22). The pooled canonical structures of the second dimension were largely dominated by two variables describing the timing of specific flow events (in order of importance) the day of minimum seasonal low flow and day of maximum streamflow) along with the 99^{th} percentile of the FDC which describes extreme low flows. Thus, this dimension also reflected the magnitude of streamflows but was more closely related to low flows. This dimension largely served to discriminate among regions within each of the green and white land use zones. The third dimension reflected in the intercepts of mean regional flood frequency regression lines and the number of discrete high streamflow events. When plotted alongside the magnitude and timing axis (dimension one), this dimension only appeared to discriminate between region 6 and the remaining groups (Figure 2-23).

2.4 Discussion

This work has demonstrated that a hydrologic classification approach based on the relatively simple variable of standardized hydrograph shape was effective at highlighting the spatial variation in streamflow regimes needed for effective hydrologic classification. Furthermore, hydrograph shape does appear to represent a powerful and parsimonious hydrologic variable which captured and described a broad set of hydrologic variables calculated from a demonstrably independent hydrologic dataset (e.g. one based on 21-day abstracted and z-score transformed long term mean annual flow records and the other based on the full time series of un-standardized actual flow records).

Cluster analysis based on hydrograph shape was successful in stratifying study watersheds into six geographically consistent regions across the forested and non forested land zones of the province. All regions had snowmelt dominated hydrographs, but each displayed regionally unique characteristics highlighting the spatial variability in streamflow regimes. Differences were most evident between the forested (green zone) portions of the province and the non-forested (white zone) parts of the province. The 3 forested regions all showed strong differences between hydrograph shapes and hydrologic characteristics. On the other hand, the 3 non-forested regions were somewhat similar to each other in terms of their hydrologic behaviour.

During the clustering process, in which multiple solutions were analyzed each with an increasing number of cluster groups, a pattern emerged in the way that groups were formed. The sequence by which groups separated from each other indicated that the greatest differences in hydrograph shape (e.g. streamflow regime) occurred primarily between green zone and white zone regions (step 2) (Table 2-2). The first major separation within the green zone was region 6 (step 4) followed by regions 5 and 1 during step 7. In the white zone, the first major group created was region 4 (step 3); which had the most unique hydrograph shape out of all 3 non-forested regions (Figure 2-10). The final remaining white zone regions did not separate until step 5, when two groups were formed adjacent and further away from the forested area creating regions 7 and 8. Among the green zone and white zone regions respectively, region 6 and 4 were the first two groups formed after the green and white land zones were stratified, indicating that these two regions had the greatest differences between regions located within forested and non-forested land zones. When hydrographs were plotted (Figure 2-10) a similar pattern in the differentiation between regions was observed. Hydrographs in green zone regions all showed strong snowmelt dominated peaks that became more variable (less distinct) moving from region 6, to 1, to 5, reflecting increased variability in the timing and magnitude of streamflows. White zone regions also had snowmelt dominated peaks however; hydrographs displayed multiple peaks which were smaller in magnitude and earlier in timing than in the green zone. Hydrographs from white zone region 4 were most different from regions 7 and 8, which had very similar shapes to each other but differed in the timing of peaks and the range of magnitudes. The sequence by which groups were formed during cluster analysis, based on hydrograph shape, was complementary to observed differences in regional hydrologic characteristics used in post-classification comparisons between regions (Table 2-1). The most significant differences in post-hoc tests of hydrologic variables were often observed between green and white zone groups (Table 2-4). Within the green zone, hydrologic characteristics of region 6 were often different when compared between regions 5 and 1, which were often more similar to each other. Likewise, in the white zone, hydrologic characteristics of region 4 were often significantly different from regions 7 and 8, which were also more similar to each other. The relative differences in the hydrologic characteristics and mean annual hydrographs between regions is reflective of the order by which regions were formed during cluster analysis, with watersheds whose hydrographs were more distinguishable being grouped first and watersheds with more variability in hydrograph shapes being grouped last.

The spatial distribution of cluster groupings was found to be consistent with hypothesised locations of hydrologic regions consistent with a strong west to east distribution in climatic and topographic controls known to be influencing regional hydrologic behaviour. Thus, while classification was based solely on surface water hydrographs it also reflected the broad differences in higher order controls on regional hydrologic variability (which is governed by gradients in climatic and physiographic controls). In region 6, all watersheds contained headwater glaciers causing this region to have notably larger streamflows for high, average and low flow conditions. The timing of streamflows was also later in region 6 resulting from delayed inputs of melt water during warmer summer months. These watersheds clearly revealed characteristics of a glacial dominated flow regime, having a single large peak occurring late in the summer when temperatures and melt rates are at their highest (Meier, 1964). Region 1, also characteristic of a high elevation snowmelt dominated regime, had a single peaked snowmelt hydrograph similar to region 6 but was lower in magnitude and earlier in timing. Region 5 covered the largest portion of Alberta’s forested area and had watersheds which were distributed at lower elevations along the lower east slopes of the province, moving north-east into the Boreal plain. Region 5 hydrographs were snowmelt dominated and contained multiple post-freshet peaks with large variability in the magnitude and timing of streamflows. The variability and spatial extent of region 5 may be an artefact of the interaction between higher order hydrologic controls (e.g. climate, geology, and topography) influencing the shape of the hydrograph. For example; in the western part of this region, large snowmelt inputs from higher elevations may be paralleled by rapid delivery of melt water occurring at the same time from lower elevations resulting from comparatively higher temperatures in the spring. Likewise, the effect of frontal or topographic precipitation along the foothills of Alberta may be similar to inputs from convective storms in the east Boreal causing multiple hydrograph peaks after snowmelt related peaks recede. Although convective storms are common across the entire province and account for almost 40 percent of summer rainfall volumes, they are more common in larger, more homogeneous terrain such as the Boreal plain (Chetner, 2003). Another factor influencing hydrologic variability in region 5 may be the spatial differences in atmospheric and sub-surface hydrologic controls; these factors may be disproportionately influencing how and when climatic inputs are routed into streamflow. Smerdon *et al.* (2005) shows evaporative flux from surface waters in the Boreal plain are a significant factor controlling relationships between precipitation, groundwater and surface water behaviour. Devito *et al.* (2005) found that high variability of catchment runoff in the Boreal plain of Albert was, to a large extent, controlled by relationships between soil water storage and evaporation and seasonal precipitation deficits influencing the hydrologic connectivity of the system.

The three hydrologic regions in the white zone (non-forested lands) of the province displayed very different hydrographs from the forested landbase, suggesting different types of hydrologic controls were influencing streamflow regimes. Region 7 was furthest away from the forested landbase (Figure 2-9) and had hydrograph peaks of successively declining magnitudes, which often rose sooner in time when contrasted to regions with similar hydrograph shapes, such as region 8. Region 8, located between region 7 and the green zone, displayed similar hydrograph shapes with region 7, but had later timing of streamflows with larger magnitudes. A possibility for these two regions being different in terms of hydrograph shape (and therefore cluster membership) may be the spatial distribution of forest cover and effects of variable canopy density on the capture and release of snow during winter months and the spring freshet. Areas with less forest cover (presumably region 7, as it is located further into lands dominated by agricultural production) would be subject to greater radiation inputs and winds causing earlier snowmelts when compared to areas with greater forest cover (more thermal insulation) in which snowmelt would be more delayed (Gelfan *et al.*, 2004; Sicart *et al.*, 2004). Region 4 hydrographs appeared characteristic of a ground water dominated flow system. Supporting this reasoning is (1) the observation of the FDC slope being comparatively flat (Figure 2-21), especially during lower flows (Gordon, 2006), and (2) receding parts of mean annual hydrographs were comparatively higher in region 4and had more gradual recession compared to other regions. The slope of the FDC can be related to the contribution of surface/ground water as watersheds with very steep FDC slopes are typically flashier due to a flow regime dominated by precipitation based events; whereas flatter FDC, due to the influence of ground water inputs, are typically more stable (Yadav *et al.*, 2007). Slopes of the regional FDC were different between regions, especially between the 3 green zone and 3 white zone regions. Regions 1, 5, and 6 all had similar slopes in comparison to regions 7 and 8 whose slopes were steeper. Region 4 had the shallowest slope of all the regions, suggesting a greater influence of ground water.

These 6 hydrologic regions clearly have unique streamflow regimes and follow spatial patterns based on the influence of higher order controls (e.g. climate & physiography); which is surprising as regions were developed from a purely hydrometric classification approach and did not include any landscape or climate based variables. The hydrologic regions identified in this work follow the spatial gradients in provincial climate characteristic, specifically precipitation and topographic patterns across. Precipitation and topography are related to each other as areas with higher elevations generally have greater precipitation (Chetner, 2003). In Alberta, areas with higher precipitation correspond to the spatial extent of regions 1, 5 and 6; which also have the highest average streamflows. If specific catchment processes can be associated with the observed regional differences in hydrology, a better understanding of the influence of higher order controls in these regions could be gained. However to accomplish this, greater understanding and analysis of the physiographic and climatic variation across hydrologic regions would be necessary.

The hydrometric classification approach presented in this work is one among two common approaches used to define homogeneous hydrologic regions. The alternative method is a landscape based approach using physiographic and climatic variables to group watersheds into regions of similar hydrologic behaviour. Landscape based approaches such as the hydrologic landscape concept of Winter (2001) approach classification in a 'top-down' hierarchy of hydrologic controls. In this method catchments are grouped by similar land surface form (upland, valley and lowland configuration), geologic structure and climate under the assumption that patterns of surface and ground water flow are associated with physiographic setting. Wolock *et al.* (2004) used the hydrologic landscape concept to delineate regions across the United States, finding regions followed spatial similarities with patterns of climate and previously established natural ecologic regions. Similarly, Golder Associates Ltd. (2006) employed a landscape based approach for hydrologic classification of Alberta, Canada; using physiographic (topography, elevation, slope, geology, soils) and climatic (temperature, precipitation, rainfall and snowfall) variables. These regions were then examined for similarities in hydrologic behaviour for a smaller sub-set of streamflow variables (mean annual runoff, 2 and 10 year flood streamflows and average February streamflow). Results from hydrologic analysis and regional comparisons did show trends, but the spatial patterns (and differences) in streamflow among regions were not as strong as expected. Difficulties were likely a result making preliminary (*a priori*) assumptions on the importance of higher order controls, thus constraining the range of hydrologic response evaluated. Furthermore, because of well established positive relationships between precipitation and mean annual runoff, this classification approach resulted in groups of watersheds with similar streamflow magnitudes closely corresponding with the natural ecologic regions of Alberta (Downing and Pettapiece, 2006). Using a somewhat different organizational approach Mwale *et al.* (2009) reported broadly similar findings to Golder (2006, *unpublished*) at a much coarser scale. Precipitation, air temperature, potential evapotranspiration and streamflow variables were used to define spatial and temporal patterns of climatic characteristics and relate them to 6 broad ecologic regions across the province. In a hydrologic context, Mwale *et al.* (2009) concluded the province could only be stratified into 2 distinct hydrologic regions; which vaguely corresponded to the green zone (forested) and white zone (non-forested) boundaries. These two Alberta based examples are evidence that assuming spatially static landscape and climatic controls likely constrains the evaluation of hydrologic variation to a coarser spatial resolution, contrasting streamflow based classification approaches. Likewise, by only examining one or two hydrologic variables well known to have positive associations with climate and physiography, very little new information on regionally specific hydrologic characteristics can be gained.

The work presented in this study was based on a fundamentally different philosophical approach to the classification process by focusing on actual (observed) watershed response to group watersheds into regions of homogeneous hydrologic behaviour and subsequently exploring these regions in terms of higher order controls. This method revealed an increased resolution in the regional patterns of streamflow across the province. By incorporating a simpler variable of hydrograph shape factor to drive the classification, unique streamflow regimes were clearly defined that reflected the spatial variability in climate and landscape across Alberta that were not evident with previously attempted landscape based approaches.

Typically, the streamflow based classification approach analysis begins with selection of relevant hydrologic variables for classification variables. These hydrologic variables are selected to represent the overall streamflow regime or tailored to meet specific management objectives. However, in a general classification approach, the potential number of streamflow variables can exceed 200 (Olden and Poff, 2003) and thus requires careful consideration and identification of which variable(s) are most suitable to reflect the hydrologic setting or objectives for the classification (Poff *et al.*, 2006). This problem is addressed by using multivariate techniques to select non-redundant variables describing most of the statistical variation. To remove some initial ambiguity of variable selection Olden and Poff (2003) organized relevant hydrologic variables into flow categories representing hydro-climatic characteristics based on hydro-geographic stream classification work of Poff (1996) (e.g. snowmelt, perennial, rainfall, intermittent streamflow regimes). Comparison between relevant hydrologic variables suggested by Olden and Poff (2003) for snowmelt dominated systems and the hydrologic variables used in this study (Table 2-1) found that variables associated with regional differences in hydrograph shape were similar. Although hydrologic variables were calculated and defined differently, measures related to mean annual streamflows; 1, 3, 7 and 30 day mean minimum and maximum streamflows and the number and durations of high and low flows closely corresponded to variables suggested by Olden and Poff (2003) to be most influential at describing streamflow variability for a snowmelt dominated system. This supports study findings that hydrograph shape factor can be used to adequately describe and classify the variability in streamflow regimes, as it captures significant differences in regional hydrologic characteristics. It must also be emphasized that an approach based on selecting statistically relevant hydrologic variables may not adequately represent important variables from an ecological or management stand point. Streamflow based approaches often have objectives of relating hydrologic regimes to ecologic indicators (e.g. community structure) for assessing hydro-ecological change from management activities (Richter *et al.*, 1996). Monk *et al.* (2007) tested the ecologic representativeness of the Olden and Poff (2003) technique for selecting non-redundant hydrologic variables and found it sufficiently addressed variables important to the ecologic structure of streams, but also suggested that incorporating a qualitative selection process, based on site specific knowledge may be just as important in deciding which variables are most representative and influential in driving the ecology of streams and rivers. My statistical approaches may not directly address important ecological variables, as hydrologic variables accounting for the most statistical variation are emphasized. However, it is possible to make inferences regarding hydro-ecological connections of these variables because the dominant hydrologic differences observed are those which are most likely driving large scale patterns of variability in community structure within streams and rivers.

2.5 Conclusion

The results of this work highlight the extreme variability in streamflow regimes that are present across the province of Alberta. The simplified approach to classification based on hydrograph shape factor revealed distinct patterns in streamflow regimes. This is evident from clear differences amongst the high water yielding areas of glacier influence and snowmelt dominated alpine/montane watersheds (regions 1 and 6) to the more variable areas of the foothills and north east Boreal forest (region 5) which are characterized by more complicated flow pathways (Devito *et al.*, 2005). These findings reinforce that an approach based on the hypothesis of a single higher order control driving hydrologic response may not be acceptable at larger landscape scales. The interaction of multiple controls may be a reasonable expectation in some regions (4, 5, 7 and 8), whereas in other regions one dominant control may be more appropriate (regions 1 and 6). A purely hydrometric approach may be more reasonable for classification because it allows the streamflow data to drive grouping of hydrologic regions, thus no *a priori* assumptions are made in the process. This streamflow based approach is conceptually simple, but poses operational challenges and may not be possible in many areas due to lack of hydrometric data. In fact, if more hydrometric data were available for the province of Alberta, greater precision may have been possible for defining regional hydrologic boundaries and there may have been greater potential to identify regions with unique streamflow regimes. Problems with sparse data records could be alleviated and the approach substantially strengthened by including physiographic and climatic variables into the process. Although the present study established a clear pattern in the distribution of streamflow regimes across the province, only broad inferences can be made regarding processes which might be influencing hydrologic behaviour in these regions. Further investigation into how these regions are unique in terms of physiography, climate and land cover would be of particular value. The single most important contribution of this work is that a classification framework based on hydrograph shape factor provides an accurate perspective in representing the regional spatial variation of streamflow regimes at a landscape scale while incorporating valuable hydrometric information important to water resource managers.

Table 2-1 List of the 36 hydrologic variables representing the overall streamflow regimes used in post classification statistical analysis between hydrologic regions.

Flow Category	Variable Name / Description	Symbol
Magnitude of annual water conditions (3)		
1	Mean annual streamflow [mm/year]*	MAQ
2	Mean half annual streamflow [mm/year]*	HalfFlwQ
3	Mean seasonal (July-September) low streamflow [mm/day]*‡	QminSLF
Magnitude and duration extreme water conditions (8)		
4	Mean annual 1-day maximum streamflow [mm/day]*	Qmax
5	Mean annual 1-day minimum streamflow [mm/day]*	Qmin
6	Mean annual 3-day maximum streamflow [mm/day]*	3Dmax
7	Mean annual 3-day minimum streamflow [mm/day]*	3Dmin
8	Mean annual 7-day maximum streamflow [mm/day]*	7Dmax
9	Mean annual 7-day minimum streamflow [mm/day]*	7Dmin
10	Mean annual 30-day maximum streamflow [mm/day]*	30Dmax
11	Mean annual 30-day minimum streamflow [mm/day]*	30Dmin
Streamflow magnitude regime (MANOVA) (13)		
12-24	13 mean annual flow duration curve variables [mm/day]*†	FDC
Timing of streamflows (4)		
25	Mean 1/2 flow day [DOY]	HalfFlwDt
26	Mean day of maximum 1-day annual streamflow [DOY]	Dmax
27	Mean day of annual minimum streamflow [DOY]	Dmin
28	Mean day of annual seasonal low streamflow [DOY]*	DminSLF
Frequency and duration of high and low streamflows (8)		
29	Mean number of high streamflows‡	NmbHF
30	Mean number of low streamflows*‡	NmbLF
31	Mean duration of high streamflows [Days]*‡	DurHF
32	Mean duration of low streamflows [Days]*‡	DurLF
33	Mean number of seasonal low streamflows*‡	NmbSLF
34	Mean duration of seasonal low streamflows [Days]*‡	DurSLF
35	Mean slope of the flood frequency regression line	FF_Slope
36	Mean intercept of the flood frequency regression line	FF_Int

Notes:
brackets [ ] indicate unit of measurement
* Indicates variable was natural log (Ln) transformed for ANOVA
** Indicates a constant was added to variable to eliminate zeros for ln transformation
† Mean annual streamflow at 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95, and 0.99 exceedance probabilities of the flow duration curve
‡ Discrete high flow events were defined by the number of events (counts) that mean daily streamflow [mm/day] exceeded the upper 10th percentile of the annual flow duration curve. Low flow events were defined by the number of events (counts) that mean daily streamflow [mm/day] exceeded the lower 90th percentile of the annual flow duration curve

Table 2-2 Sequence of major spatial separations observed in cluster groupings as larger groups were selected for multiple cluster analysis outputs

Clustering Step	Description of sequence of cluster group separation
1	213 stations (whole province) in one group, a small group of outliers (2 stations in extreme south AB in the white
2	Forested region (all 143 stations) separated from white zone region (now in 2 groups composed of 2 & 68
3	Same as above, but white zone separated into 3 groups (2 stations in south, 6 stations in central, and 62
4	Green zone splits (9 stations West Rocky Mountians, 136 remaining). White zone remains as above
5	Green zone remains as above. White zone; the 62 stations group [step 3] splits into 2 groups (39 station group closer to green zone [west], 23 station group further away [east] from green zone).
6	Green zone, the 136 stn. Group [4] is split into 2 groups (134 station group, 2 station group in extreme southern AB). White zone remains as above
7	Green zone: 134 station Group [step 6] splits into 2 groups (72 station Rocky Mtn. group, 62 station Lower foothills & boreal group). White zone remains as above
8	Green zone remains as above. White zone: the 6 station group in central AB splits into 2 groups of 3 stations
9	Green zone remains as above. White zone: the 2 station southern group [step 1] splits in into 2 x 1 station groups.
10	Green zone remains as above. White zone: the 39 station group near green zone group [step 5] splits into 2 groups (24 station northern AB group, 15 station central AB).
11	Green zone remains as above. White zone: the 23 station group further east of green zone [step 5] splits in into 2 groups (17 station northern group, 6 station north-central group).
12	Green zone remains as above. White zone: the 24 station northern AB group [step 10] splits into 2 groups (23 stations remain in the north, 1 outlier)
13	Green zone: the 72 station Rocky Mtn. group splits into 2 groups (36 station northern Rockies group, and 36 station southern Rockies group). White zone remains as above.

Table 2-3 Canonical structures representing the correlations between hydrograph shape variables with the highest loadings for the first 4 canonical functions. The percent variance explained by each function (dimension) is shown the bottom of the table. (+) and (-) denotes a positive or negative correlation between individual variables within each function

Canonical Function 1	Canonical Function 2	Canonical Function 3	Canonical Function 4
(+) Period 8, May/June	(-) Period 6, April	(-) Period 12, August	(-) Period 7, May
(-) Period 5 , March/April	(+) Period 3, February	(-) Period 13, September	(+) Period 12, August
(+) Period 9, May/June			
(-) Period 4, March			
(-) Period 6, April			
Variance explained (%)			
69.1	19.4	7.5	2.9

Table 2-4 ANOVA and HSD Post-hoc test results (α = 0.05) of differences between classified regions and hydrologic variables (not including 13 FDC variables). Dash (?) denotes to lack of significance in ANOVA or post hoc tests. For the number of seasonal low streamflows (NmbSLF) there were no occurrences of low flows for region 6.

				Post-hoc tests					
Variable	**F-stat**	**d.f.**	**p value**	**Region 6**	**Region 1**	**Region 5**	**Region 8**	**Region 7**	**Region 4**
MAQ	84.30	210	< 0.001	a	b	c	d	e	de
HalfFlwQ	84.30	210	< 0.001	a	b	c	d	e	de
QminSLF	165.07	210	< 0.001	a	b	c	d	e	bcde
HalfFlwDt	141.64	210	< 0.001	a	b	b	c	d	bcd
Dmax	101.76	210	< 0.001	a	b	b	c	d	cd
Dmin	1.34	210	0.248	–	–	–	–	–	–
DminSLF	56.60	210	< 0.001	a	b	bc	cde	bcd	e
Qmax	18.82	210	< 0.001	a	a	b	bc	bc	d
Qmin	27.04	210	< 0.001	a	a	b	c	c	abc
3Dmax	22.43	210	< 0.001	a	a	b	c	c	c
3Dmin	27.20	210	< 0.001	a	a	b	c	c	abc
7Dmax	28.73	210	< 0.001	a	b	c	d	d	d
7Dmin	27.45	210	< 0.001	a	a	b	c	c	abc
30Dmax	56.36	210	< 0.001	a	b	c	d	d	d
30Dmin	33.20	210	< 0.001	a	a	b	c	c	abc
NmbHF	4.34	210	0.001	c	a	a	a	ab	abc
NmbLF	1.62	210	0.155	–	–	–	–	–	–
DurHF	6.21	210	< 0.001	c	a	ab	a	ab	abc
DurLF	1.76	210	0.123	–	–	–	–	–	–
NmbSLF	4.65	210	< 0.001	–	a	ac	ab	ab	a
DurSLF	0.46	79	0.768	–	–	–	–	–	–
FF_Slope	3.76	210	< 0.001	abc	a	ab	bc	bc	d
FF_Int	16.31	210	< 0.001	a	b	bc	cd	d	cd

Table 2-5 Canonical structures representing correlations between hydrologic variables with the greatest loadings for the first 4 canonical functions. The percent variance explained by each function (dimension) is shown the bottom of the table. (+) and (-) denotes a positive or negative correlation for individual variables within each function.

Canonical Function 1	Canonical Function 2	Canonical Function 3	Canonical Function 4
QminSLF (+)	DminSLF (+)	FF_int (-)	Dmax (-)
Half_FlwDt (+)	Dmax (-)	NmbHF (-)	QminSLF (+)
FD_0_4 (+)	FD_0_99 (+)		
FD_0_5 (+)			
Dmax (+)			
FD_0_3 (+)			
FD_0_6 (+)			
MAQ (+)			
HalfFlwQ (+)			
Variance explained (%)			
70.7	14.4	7.7	4.1

Figure 2-1 Map of Alberta showing 1059 candidate study catchments (black dots) and 4 study landbase zones; (1) green zone (forested landbase), (2) white zone (agricultural landbase), (3) 80km buffer surrounding the green zone, and (4) 100km buffer around the province.

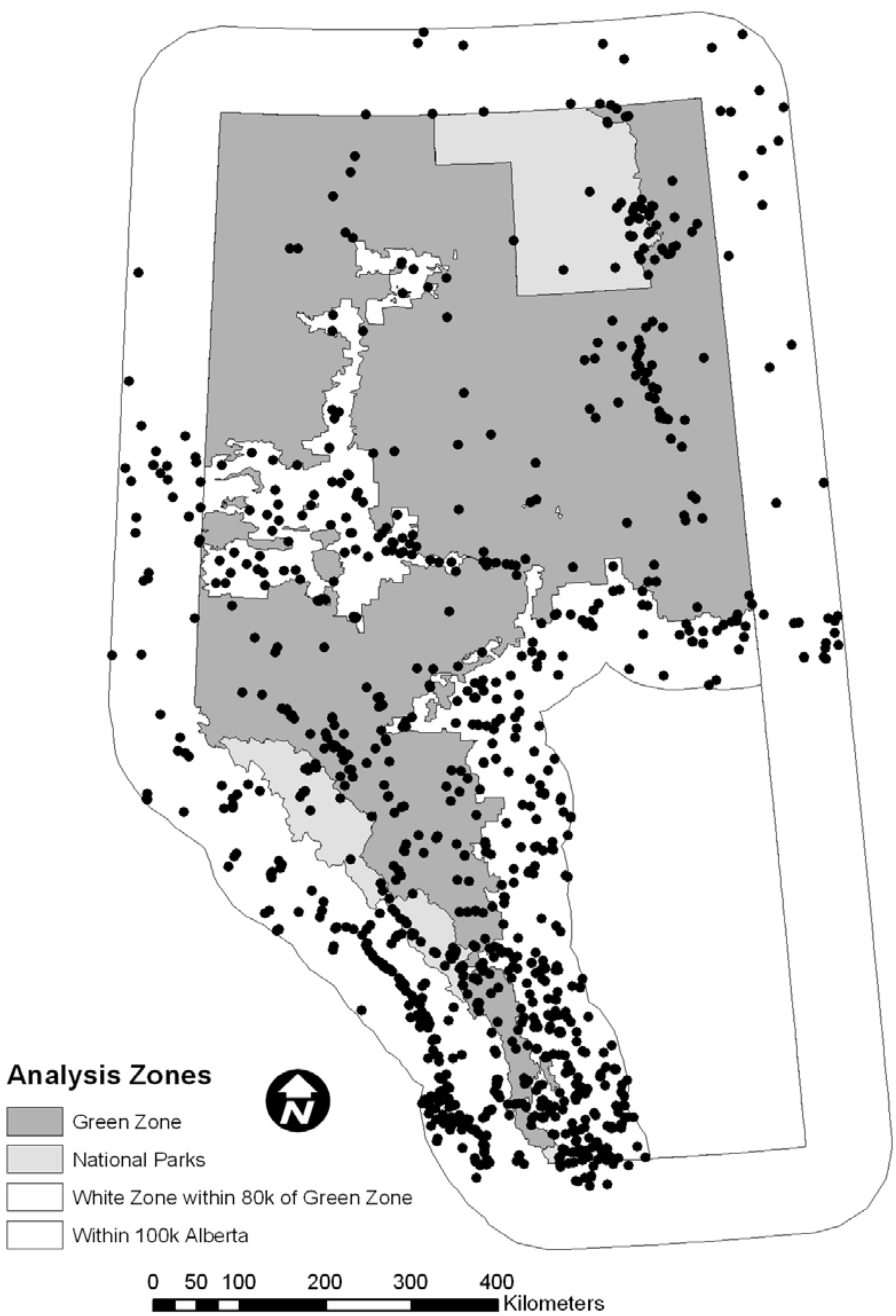


Figure 2-2 Map of Alberta showing 215 final study catchments (black dots) and 4 study landbase zones; (1) green zone (forested landbase), (2) white zone (agricultural landbase), (3) 80km buffer surrounding the green zone, and (4) 100km buffer around the province.

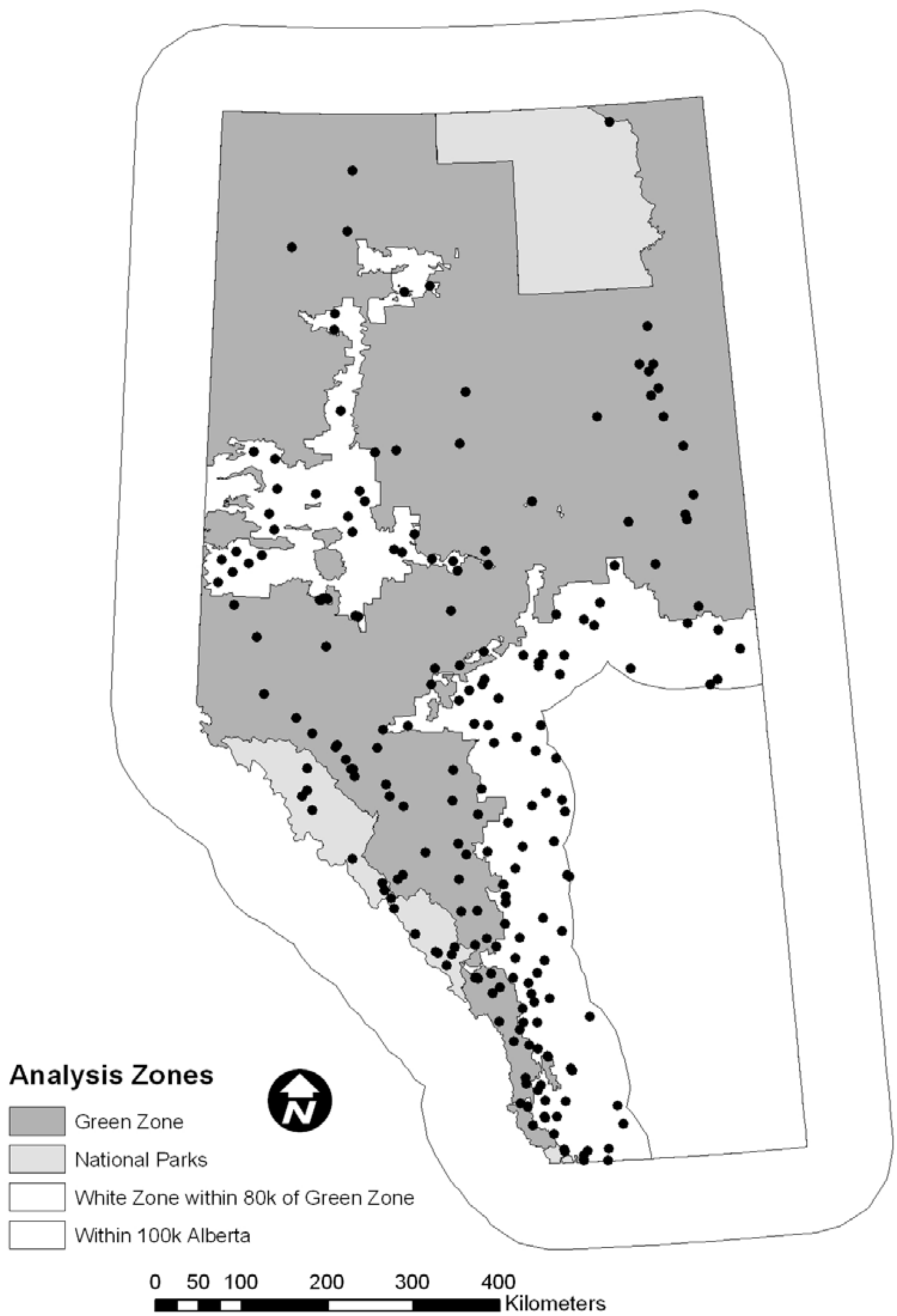


Figure 2-3 Frequency distribution of study watersheds by watershed area (in square kilometres). Dashed vertical line shows the mean watershed area for all study watersheds.

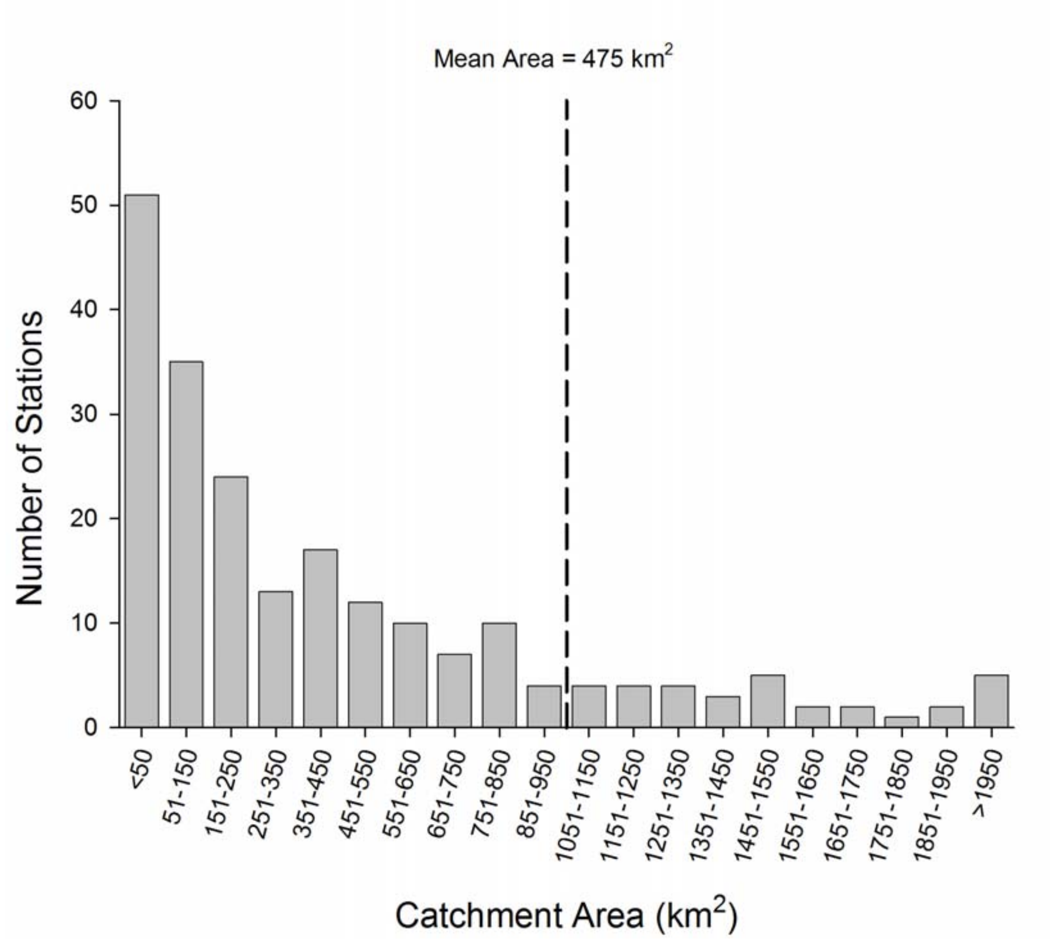


Figure 2-4 Frequency distribution of study watersheds by hydrometric record length in years. Dashed vertical line shows the mean record length for all hydrometric stations.

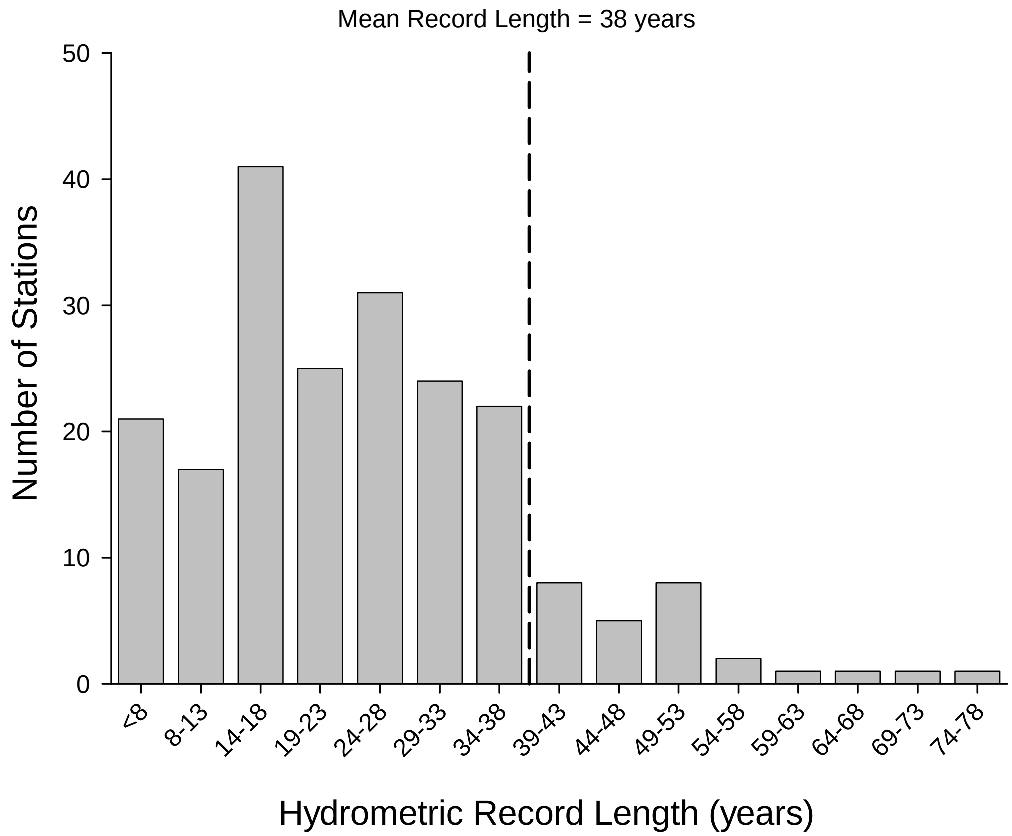


Figure 2-5 Bar-plots showing time periods of active hydrometric data collection (historical and current) for 215 study watersheds.

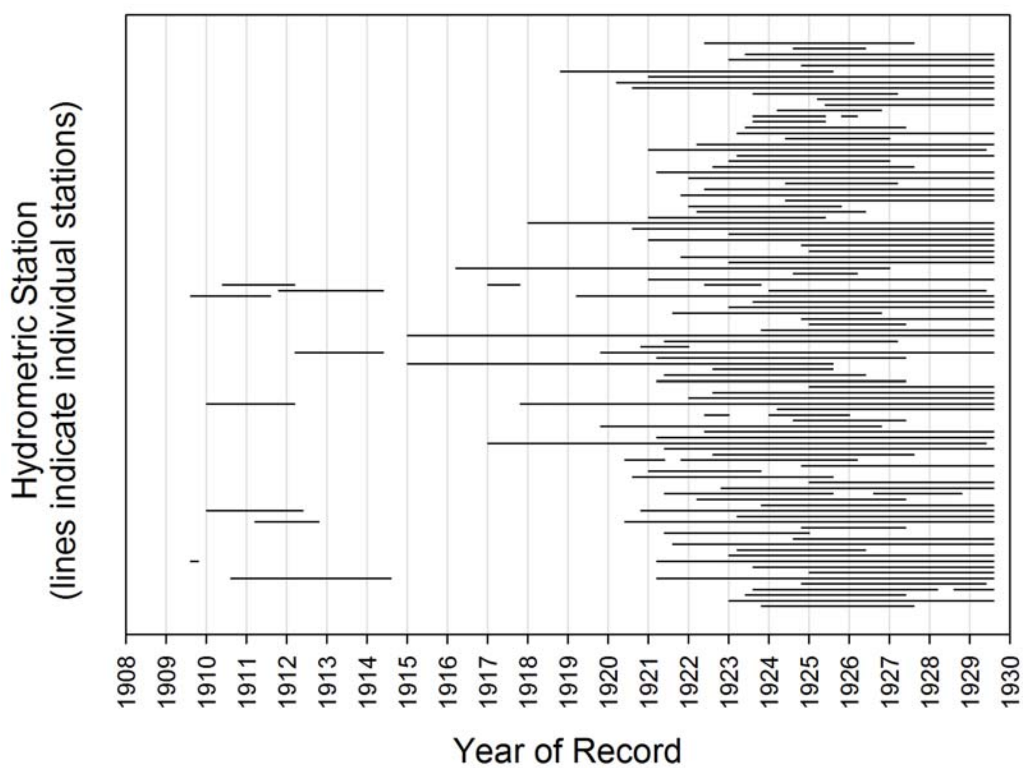


Figure 2-6 Mean annual hydrograph from a seasonal hydrometric record showing baseflow estimation during winter months that are missing streamflow observations. Solid line shows actual discharge record in mm/day and dashed line is estimated streamflow (mm/day) using baseflow recession constant.

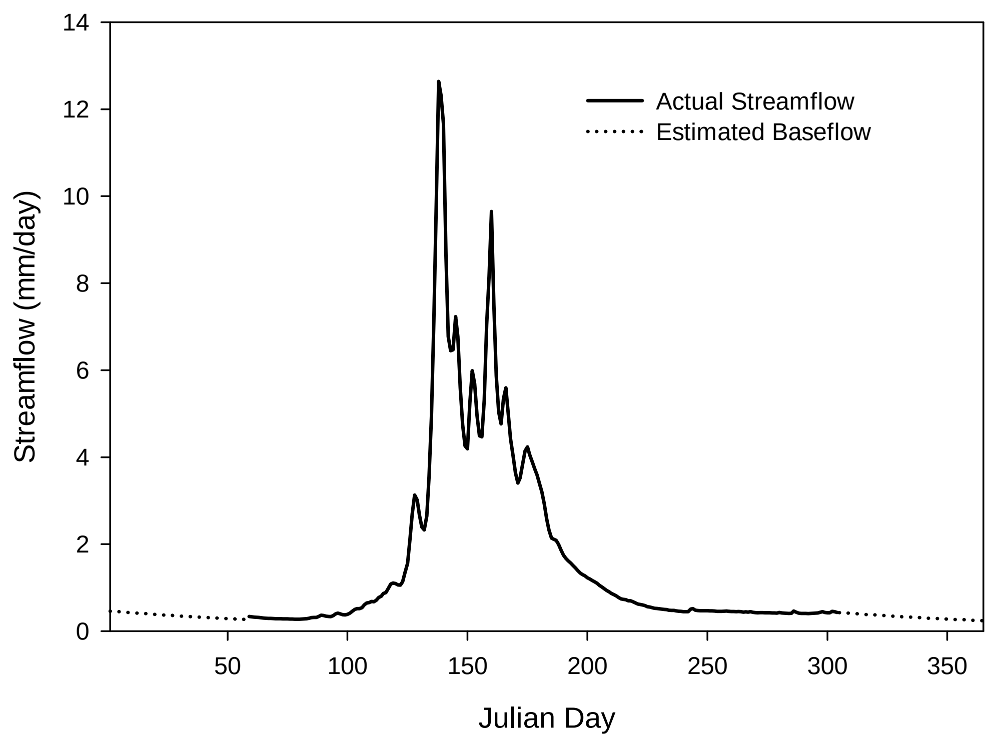


Figure 2-7 Graphs of four cluster validation measures used for selecting the optimal number of groups between different cluster solutions; (a) R-squared, (b) proximity coefficient of the agglomeration schedule, (c) semi partial R-squared and (d) dendrogram distance values.

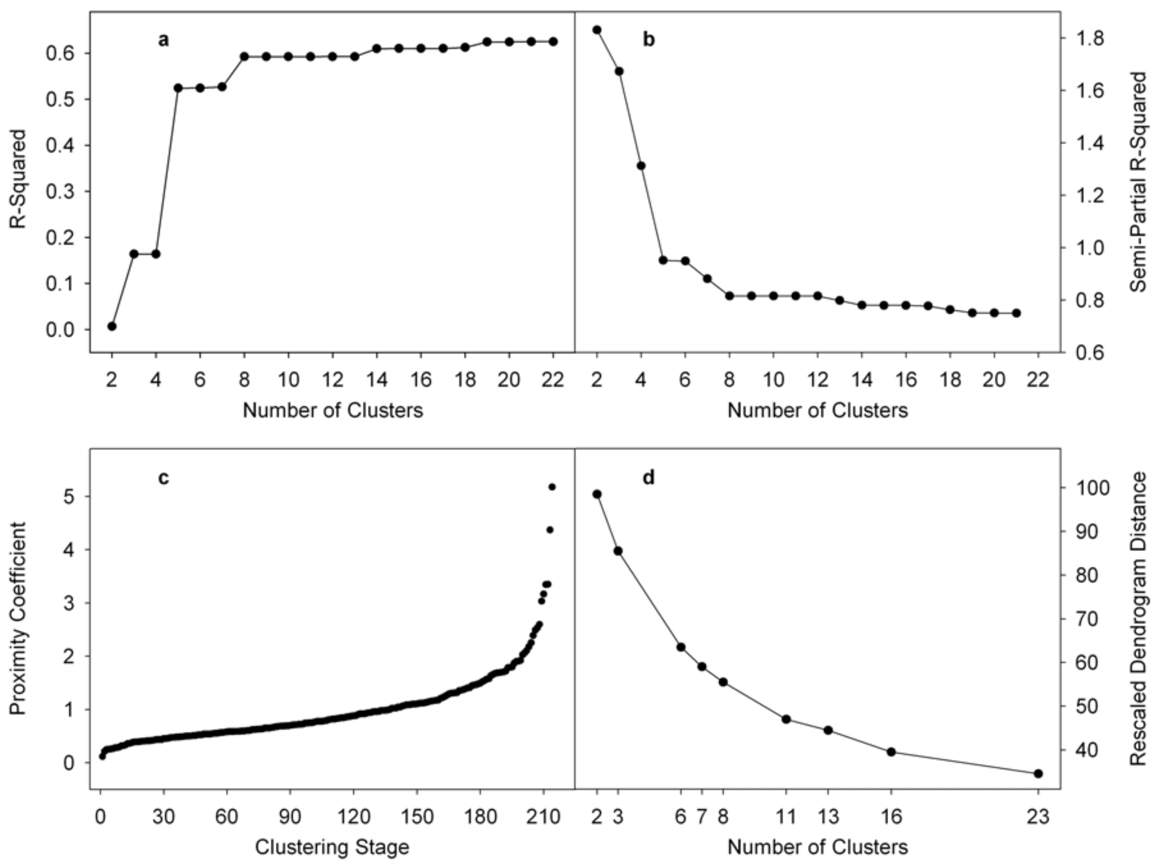


Figure 2-8 Canonical scores of significant hydrograph shape variables used in cluster analysis for the first and second canonical functions showing the separation between hydrologic regions in multivariate space. Variables listed on each axis are those accounting for most of the variance of that function.

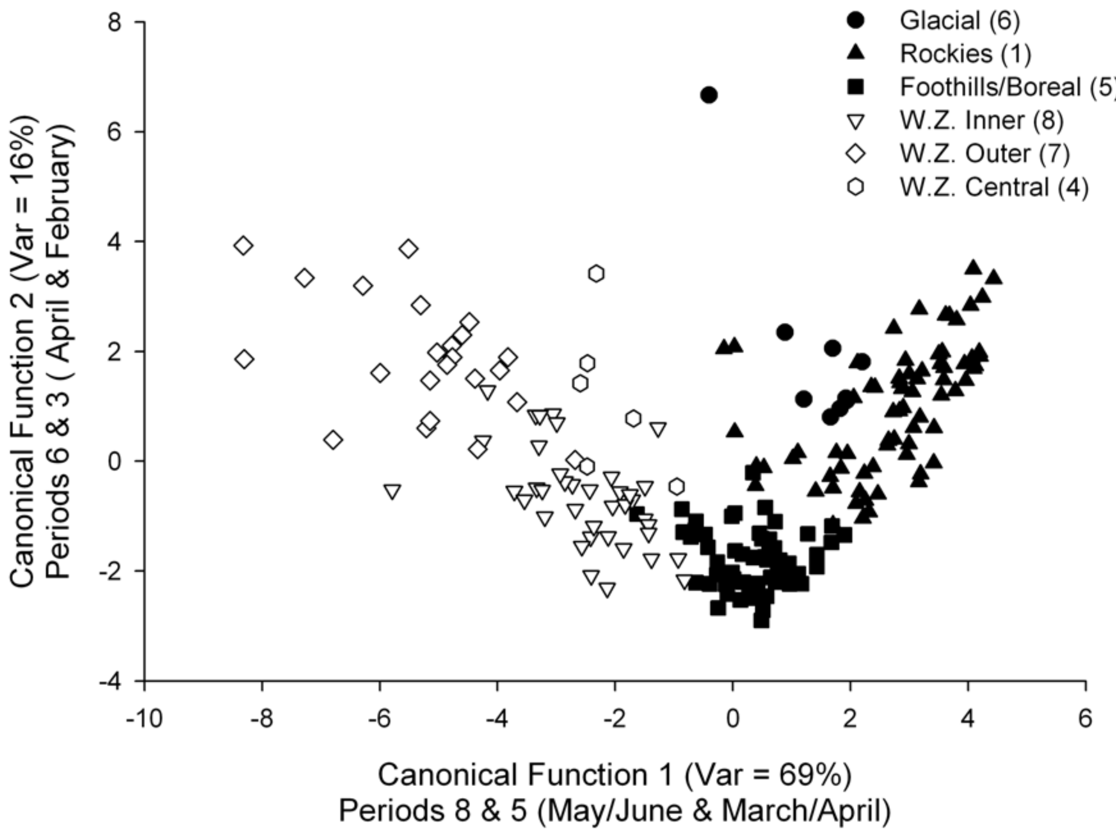


Figure 2-9 Map of Alberta showing six primary hydrologic regions from the eight group solution of hierarchical cluster analysis using hydrograph shape factor variables. The light grey area denotes the boundary between green zone and national park lands from the white zone.

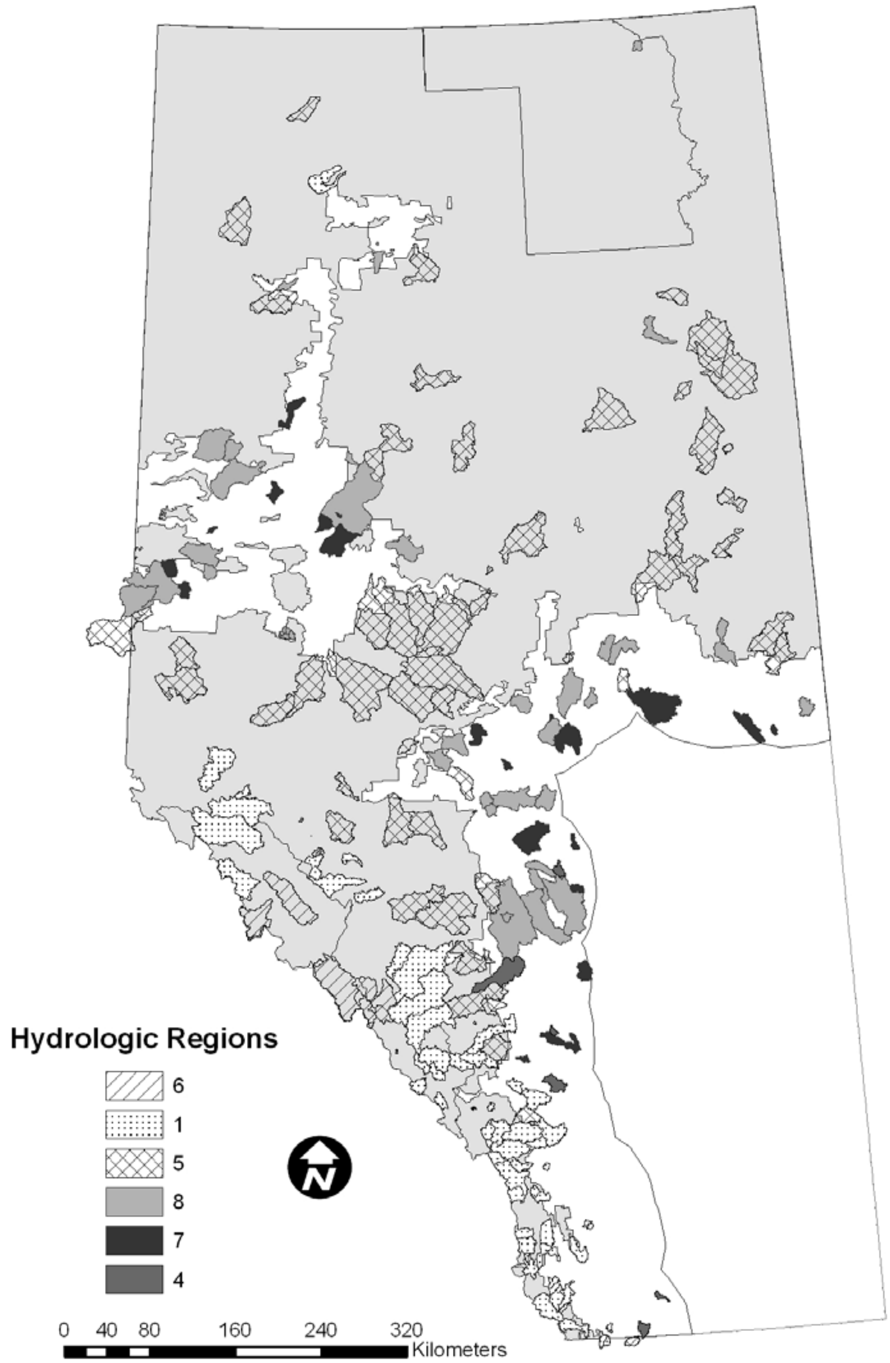


Figure 2-10 Hydrographs grouped by final cluster membership showing averaged cumulative streamflows (mm) over 21 day periods for the six identified hydrologic regions.

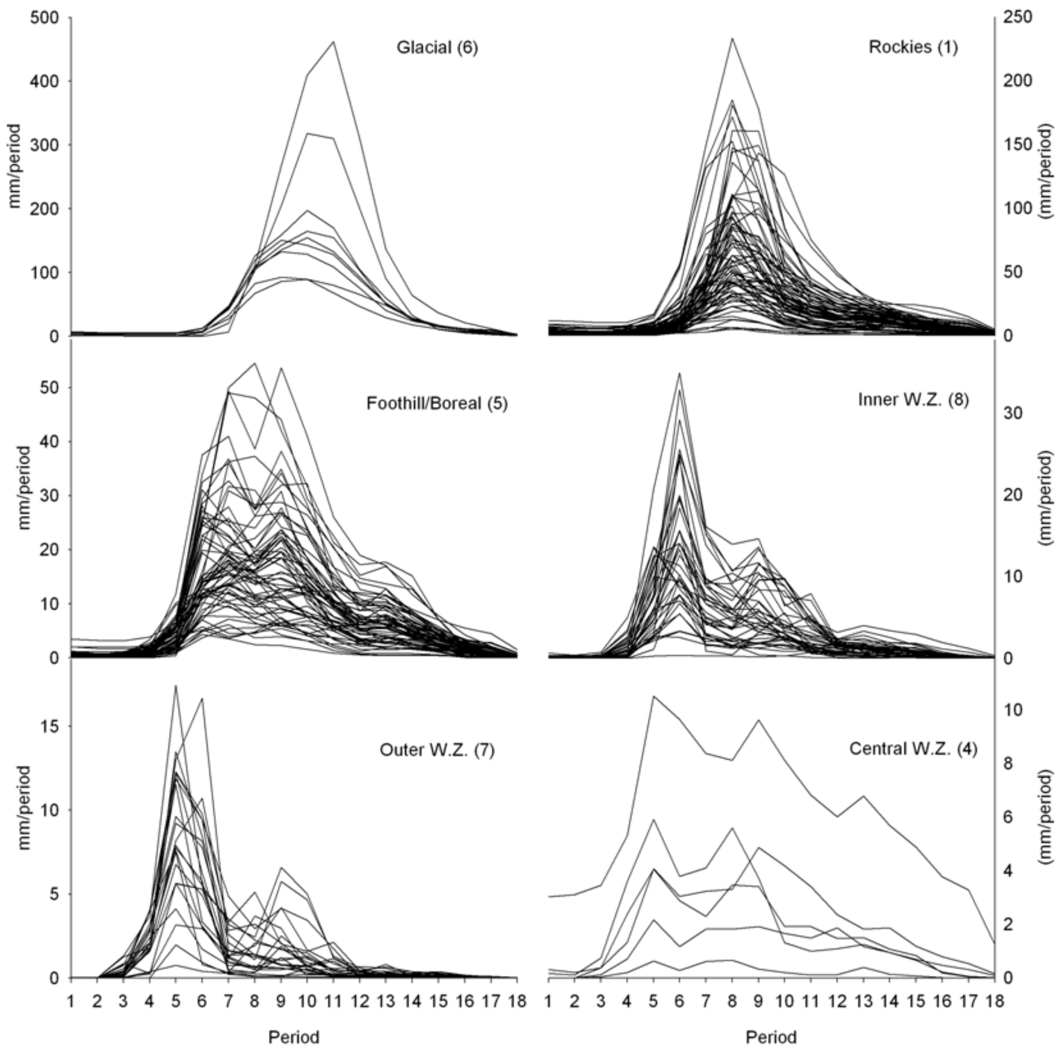
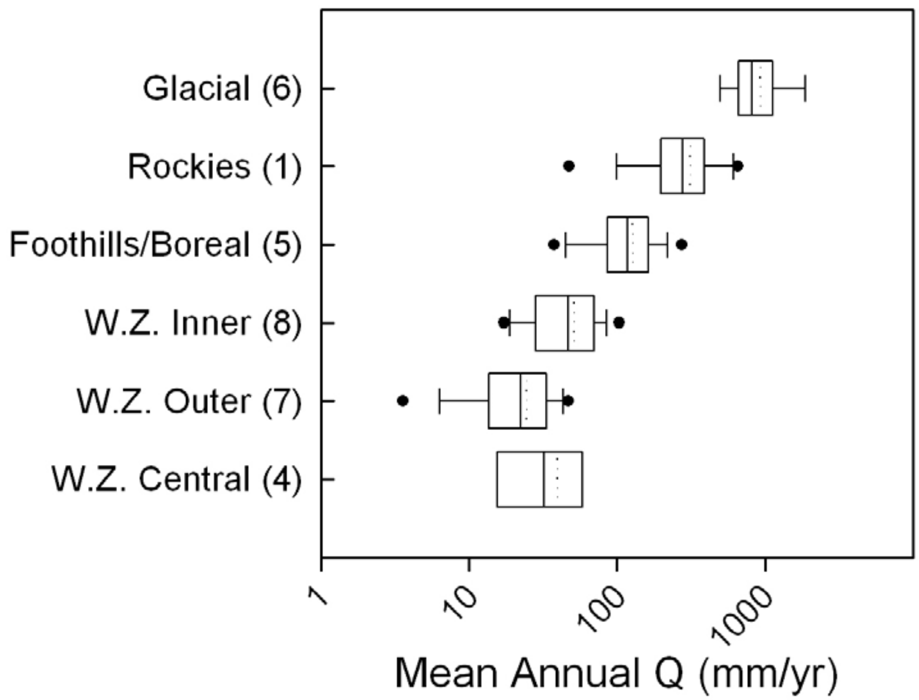
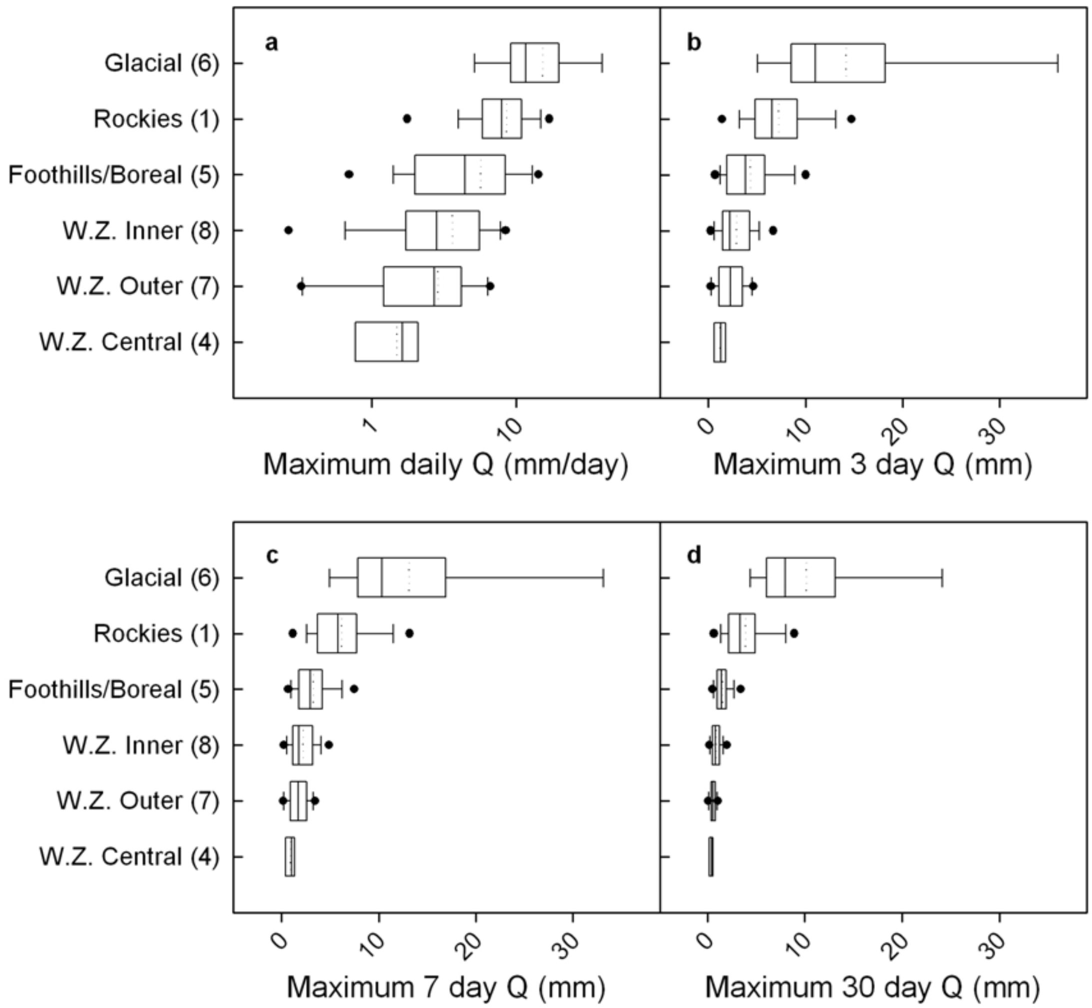


Figure 2-11 Box plot[1] of mean annual streamflow (log scale) by hydrologic region (mm/yr).



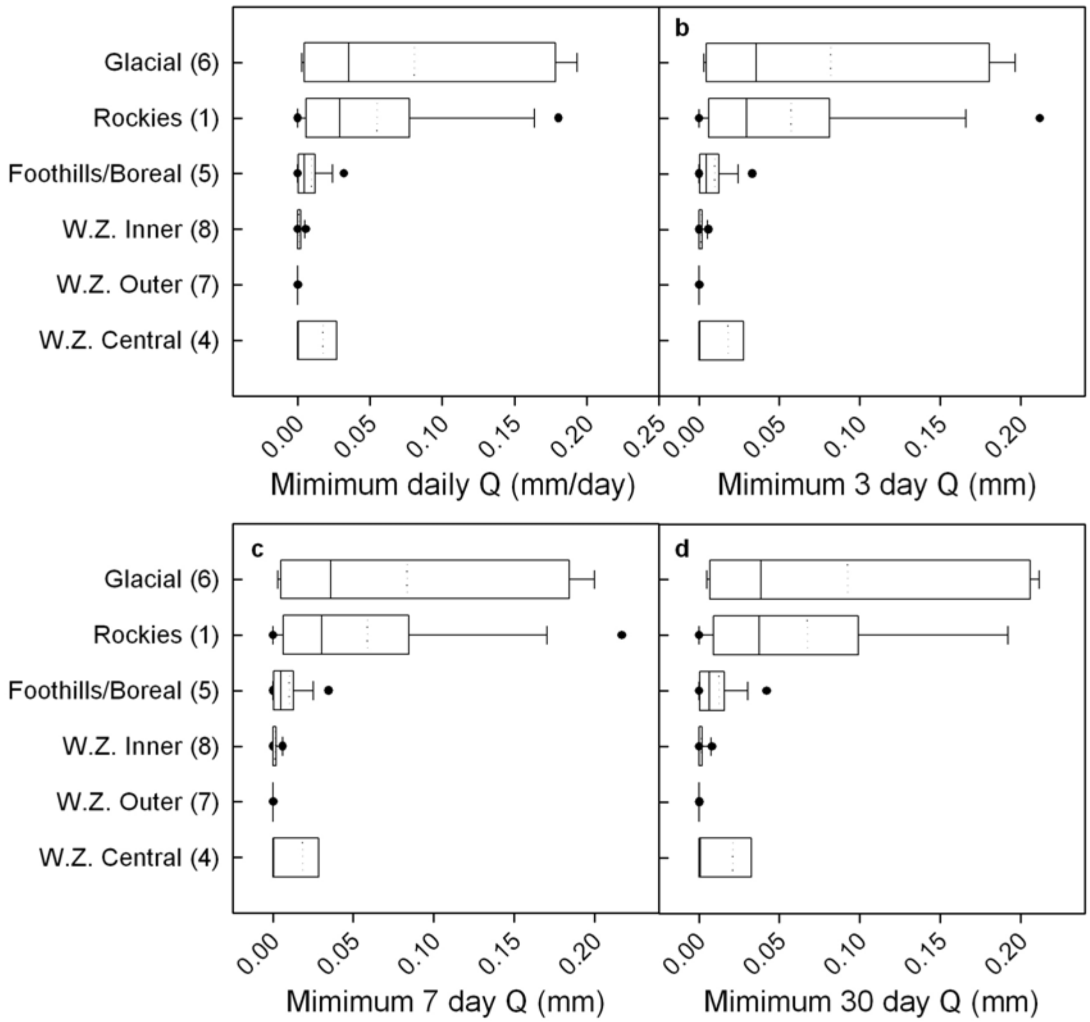
[1] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-12 Box plot[2] of (a) mean maximum daily streamflow (log scale), (b) mean maximum 3 day streamflow, (c) mean maximum 7 day streamflow, and (d) mean maximum 30 day streamflow.



[2] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-13 Box plot[3] of (a) mean minimum daily streamflow, (b) mean minimum 3 day streamflow, (c) mean minimum 7 day streamflow, and (d) mean minimum 30 day streamflow.



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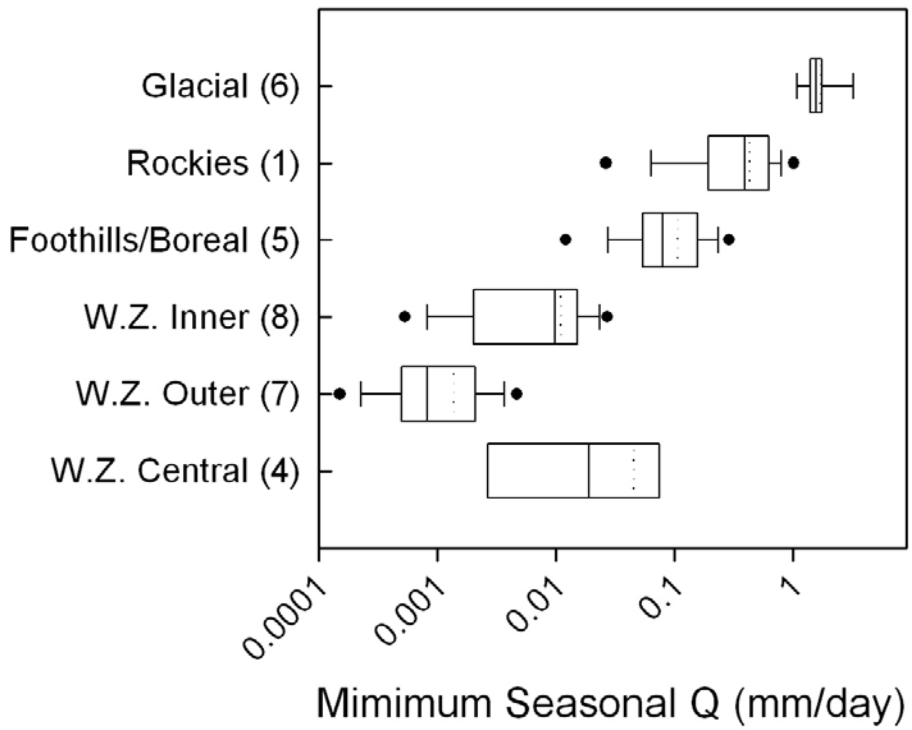
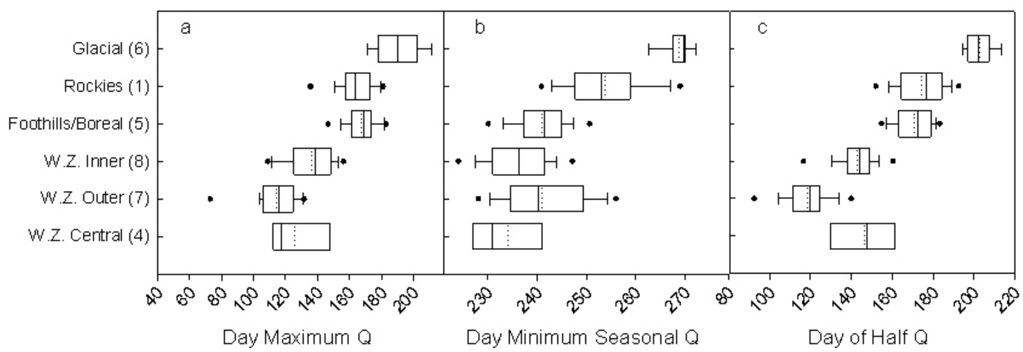
[3] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-14 Box plot[4] of mean minimum seasonal (July - September) streamflows (log scale) by hydrologic region (mm/day).



[4] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-15 Box plot[5] of (a) Julian day of maximum annual streamflow, (b) Julian day of minimum annual seasonal low streamflow, and (c) Julian day of half annual streamflow



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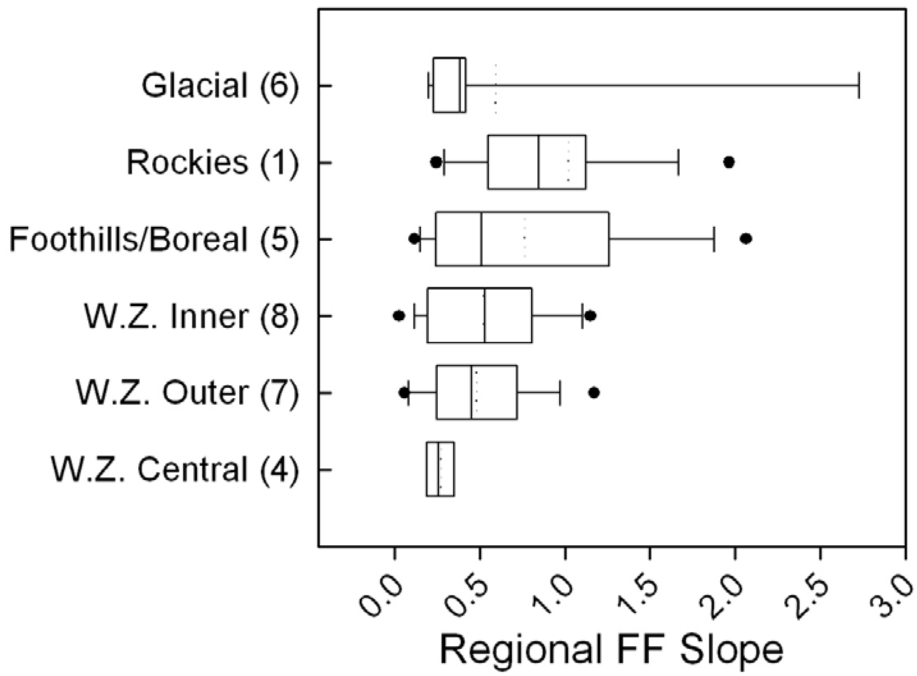
[5] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-16 Box plot[6] of the mean slope of the regional flood frequency regression line by hydrologic region (mm/day).



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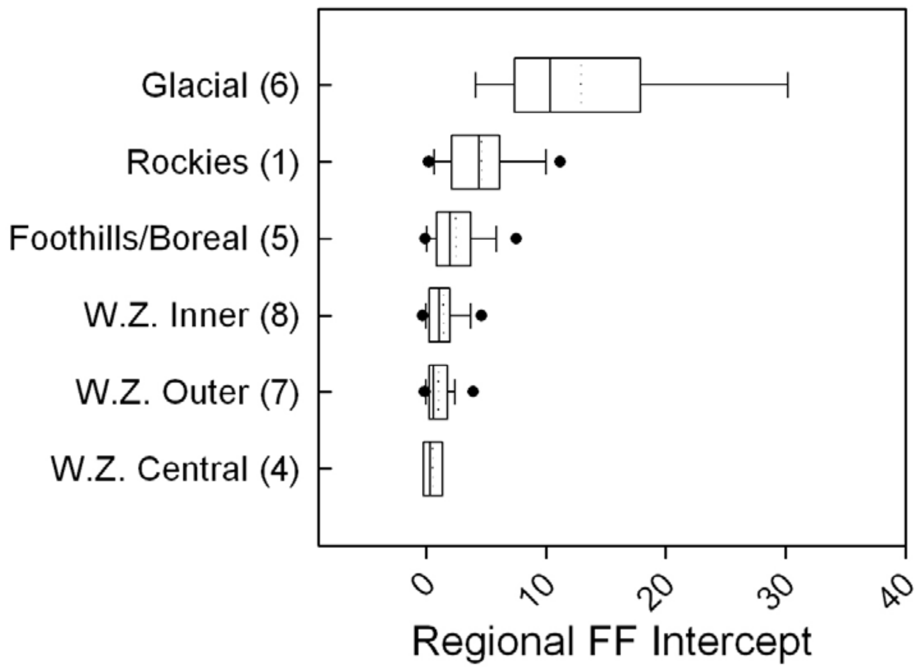
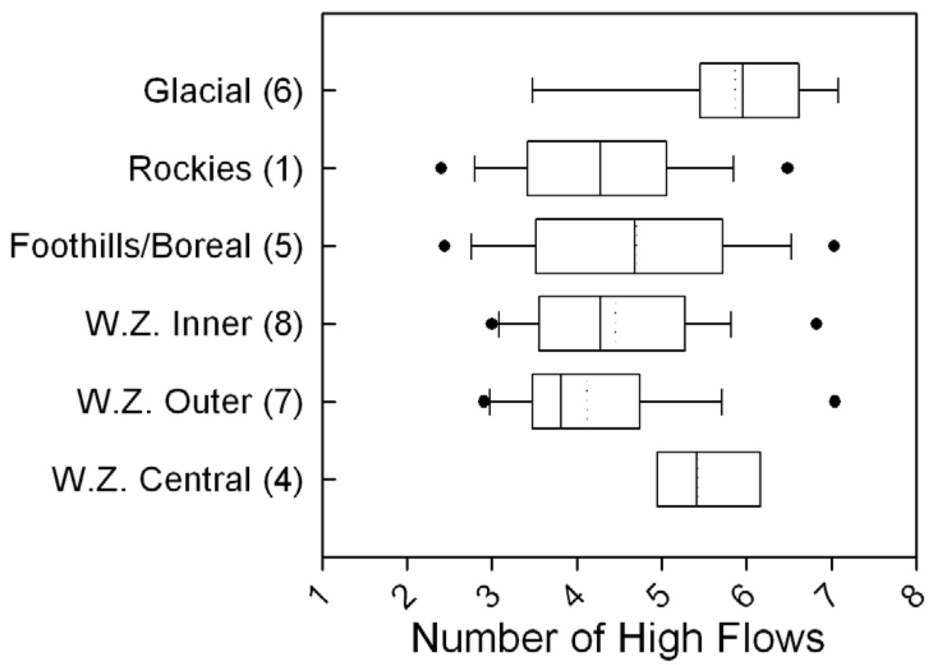
[6] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-17 Box plot[7] of mean intercept of the regional flood frequency regression line by hydrologic region (mm/day).



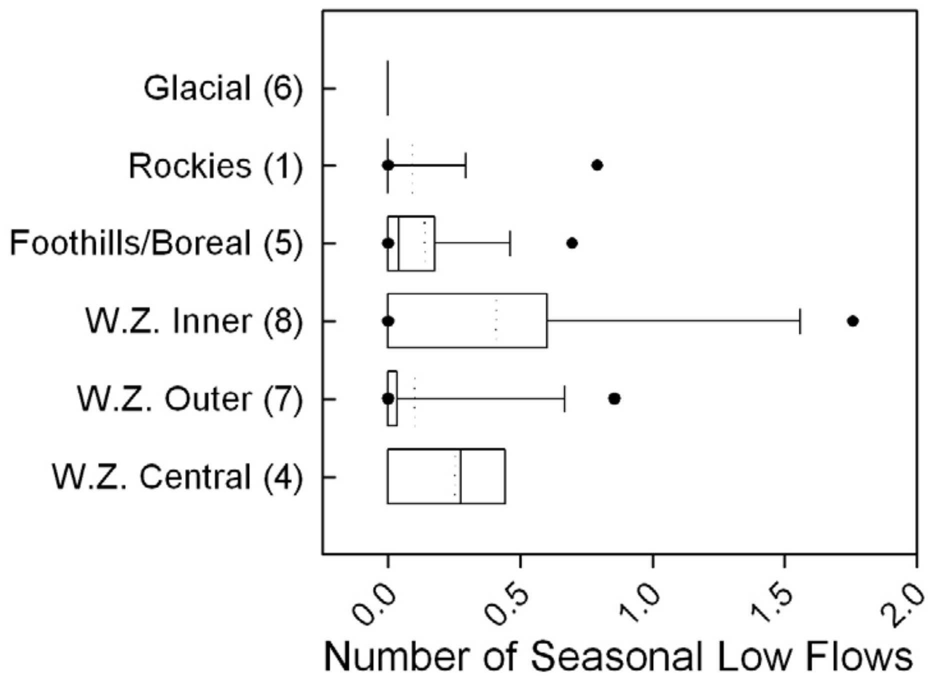
[7] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-18 Box plot[8] of the mean number of discrete high flow events (> = the 90th percentile of the regional flow duration curve [FDC] exceedance probability) by hydrologic region.



[8] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-19 Box plot[9] of the mean number of discrete seasonal low flow events (< = the 10th percentile of the regional flow duration curve [FDC] exceedance probability) from July to September by hydrologic region. For region 6 no discrete seasonal low flow events were observed.



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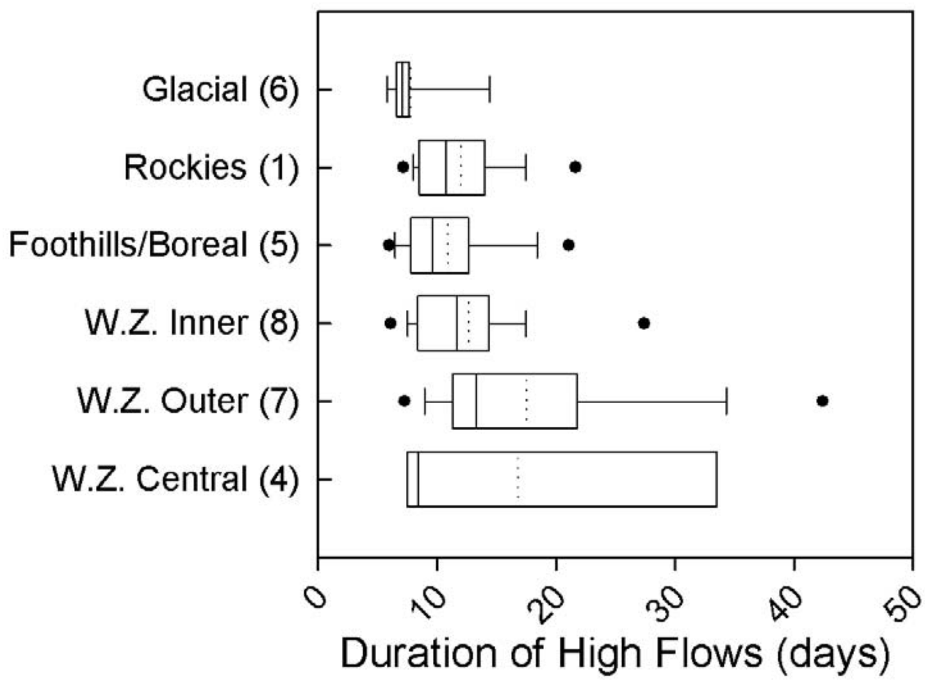
[9] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-20 Box plot[10] of mean duration of high flow events (> = the 90th percentile of the regional flow duration curve [FDC] exceedance probability) by hydrologic region.



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[10] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 2-21 Mean flow duration curves by hydrologic region. X-axis denotes the probability that a given streamflow value (mm/day) (Y-axis) will be exceeded on any given day for the region of interest. Low exceedance probabilities represent high flows with a lower probability of occurring (on any given day), whereas high exceedance probabilities represent low flows with a higher probability of occurring (on any given day).

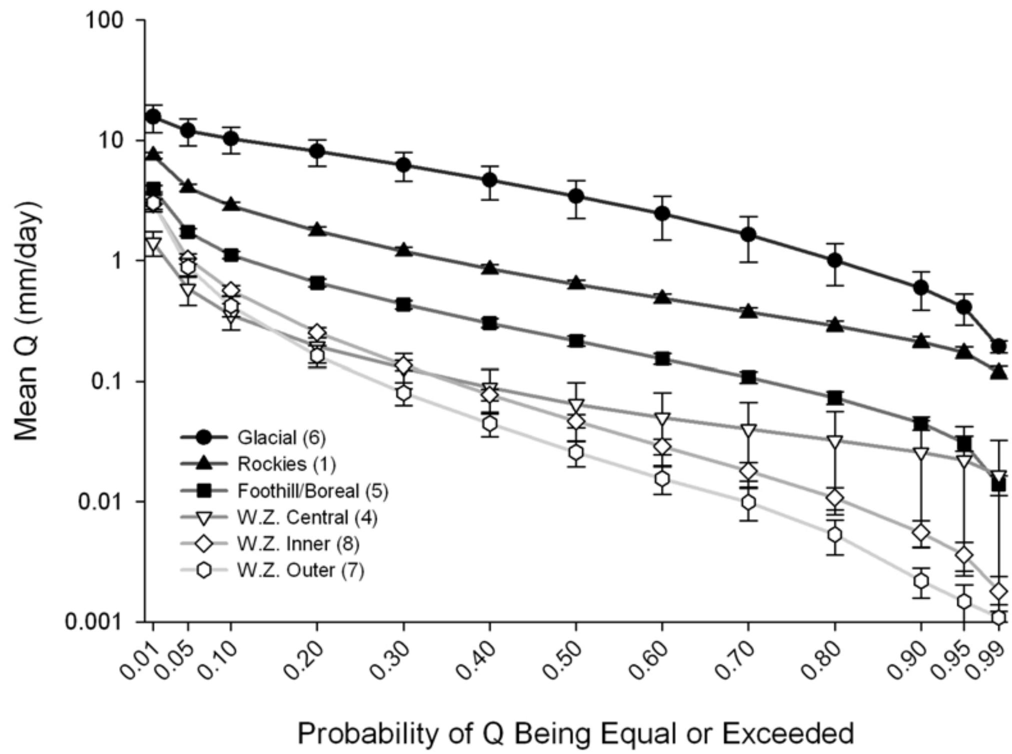


Figure 2-22 Canonical scores of hydrologic variables for the first and second canonical functions showing the separation between hydrologic regions in multivariate space. Variables listed on each axis are those accounting for most of the variance within the function.

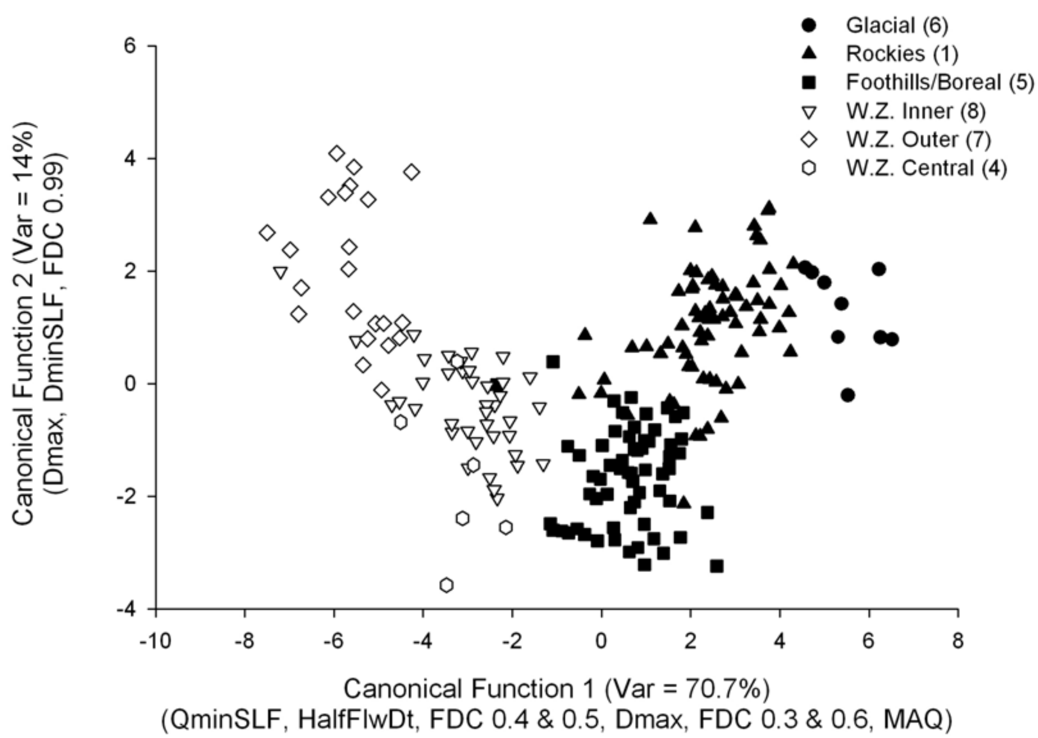
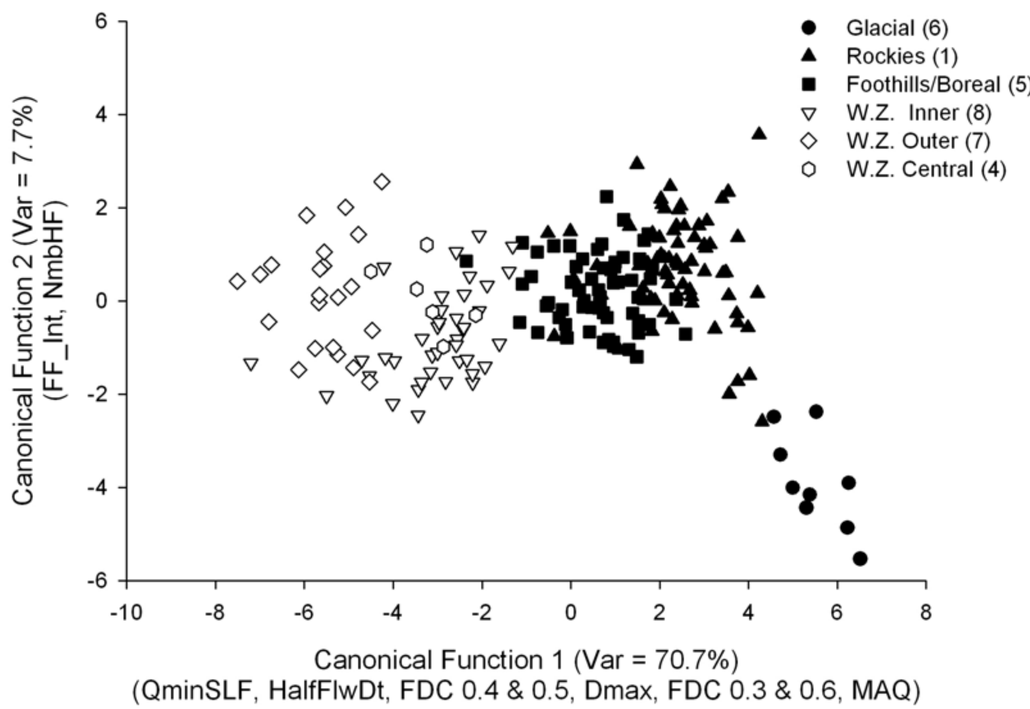


Figure 2-23 Canonical scores of hydrologic variables for the first and third canonical functions showing the separation between hydrologic regions in multivariate space. Variables listed on each axis are those accounting for most of the variance within the function



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Chapter 3: Catchment Characteristics and Land Cover of Alberta's Forested Hydrologic Regions

3.1 Introduction

The goals of hydrologic classification have often focused on indentifying the dominant controls regulating hydrologic behaviour through understanding the similarities and differences between catchments. Once dominant controls are identified they can be extrapolated to ungauged catchments for predicting streamflow or incorporated into hydrologic models to help explain the general hydrologic behaviour of catchments (McDonnell and Woods, 2004). This physical basis for classification relies on quantifying catchment characteristics regulating hydrologic behaviour in place of using hydrometric data. This has been applied in conceptual models such as hydrologic landscape regions (HLRs) of Winter (2001) or the hierarchically organized hydrologic response units (HRUs) of Devito *et al.* (2005). Landscape based characterization of hydrologic response focuses on the fundamental controls regulating streamflow response to infer hydrologic similarity. First order controls influencing catchment response are primarily those of climate forcing as precipitation drives the entire water cycle. In addition to climate, additional catchment characteristics such as the physical shape of catchments (Black, 1972) to topographic indices of slope and relief and catchment attributes such as area, drainage density and stream length (Murphy *et al.*, 1977) have been used for classification. More recent work has attempted to integrate multiple attributes such as climate, geology and land surface form using spatial extrapolation (Wolock *et al.*, 2004). This landscape based approach has been proven successful across large scales and across different hydro-climatic settings; however one of the challenges of this technique is selecting the most meaningful variables so that predictive models do not become over parameterized. Highly parameterized and complex models often lack transferability to other regions representing different physiographic and/or climatic settings.

The alternative to a landscape based classification approach is to use historical streamflow data. Streamflow based methods are often used to explore hydrologic variability and develop ecological relationships for management purposes (e.g. environmental flow standards) (Poff *et al.*, 2010). The advantage of a streamflow based classification approach is the potential for identification of distinct streamflow regimes at multiple spatial scales with additional benefits of being directly associated with the landscapes and ecological communities within and around them (Poff and Ward, 1989). Using streamflow to classify catchments integrates all of the higher order hydrologic controls (e.g. climate, physiography) that influence streamflow response and if streamflow data is available, strong relationships between physical catchment characteristics and climate should be evident. These relationships allow physiographic characteristics and streamflow to be examined for co-variance to identify the dominant controls regulating streamflow response. Likewise, catchments containing similar streamflow regimes can be examined in a physiographic context and the hydrologic / physiographic variability can be described to obtain more complete understanding of catchment response in different physiographic or climatic settings.

3.1.1 Objectives

The broad objective of this study was to examine the differences in physical attributes of catchments between hydrologic regions developed in chapter two and relate physiographic characteristics to differences in hydrologic behaviour among these regions. Specifically, objectives were to (1) characterize the regional variation in catchment physiography and land cover classes between hydrologic regions using digital elevation models (DEM) and remotely sensed land cover data, (2) examine the covariance between the physiographic and hydrometric characteristics across hydrologic regions, and (3) use these results to examine how catchment physiography and land cover may be influencing regional differences in streamflow regimes at a landscape level scale.

3.2 Methods

3.2.1 Study regions

In chapter two, a total of 211 study catchments located within and adjacent to the forested portion of the province were classified into homogeneous groups by cluster analysis using 18 variables related to the shape factor of the long term surface water hydrograph. This analysis identified six geographically distinct regions with hydrograph shapes that reflected a spatial gradient in streamflow regimes across Alberta’s forested lands from west to east (Figure 3-1 and 3-2). These six hydrologic regions were used as the study groups for comparing spatial differences in physical catchment characteristics and assessing the covariance with regional hydrologic variables.

3.2.2 Spatial data assembly

3.2.2.1 Physical catchment characteristics

Physical catchment characteristics (Table 3-1) were calculated for each study catchment using digital elevation models (DEM) acquired for Alberta, British Columbia (http://www.geobase.ca) and the northern part of Montana, USA (http://seamless.usgs.gov/index.php) at a spatial resolution of 50 meter grid cell size (ESRI ArcMap 2006, Version 9.2). Catchment characteristics were selected to reflect a range of catchment variables controlling hydrology at a landscape scale. Thus, many parameters related to drainage networks and stream morphology (e.g. sinuosity, stream order, bifurcation ratios) and associated catchment descriptors (e.g. catchment shape) were not included in the analysis. Variables were also selected based on their simplicity of calculation and their interpretability. An overview of the hydrologic importance of selected catchment characteristics and their calculation is described briefly below.

Catchment area

The size of a catchment is positively associated with the number of streams in a catchment, their size and how much water is produced (Gordon, 2006). Area can also have considerable effects on specific hydrologic characteristics such as the generation and duration of peak streamflow magnitudes. For example, smaller catchments are more likely to have precipitation falling across their entire area, resulting in higher storm discharges with shorter lag times compared to larger catchments which may only be partially inundated by a similar rainfall event; thus, increasing response time and moderating peakflows (Black, 1996). Catchment area was calculated as the gross area (km^2) of the catchment above the hydrometric gauging location.

Elevation

Elevation influences precipitation by causing air masses to release moisture as they rise due to atmospheric cooling (orographic effect), resulting in catchments at higher elevations receiving greater amounts of precipitation. These higher elevation catchments generate larger streamflow magnitudes and are more likely to have extended streamflows due to melt from a greater contribution of precipitation in the form of snow. The proportion and seasonal timing of rain and/or snow will influence the hydrologic characteristics of the catchment. Mean elevation was calculated as the average elevation across the entire catchment above sea level in meters (MASL).

Aspect

Aspect influences spatial patterns of precipitation and the distribution of vegetation which can modify the hydrologic characteristics of a catchment (Gordon, 2006). For example, northern slopes are more insulated from radiation and typically have greater vegetation and more developed soils. This can extend snowmelt runoff volumes over time; possibly reducing the flashiness of peakflows in catchments with more northerly aspects (Black, 1996). Aspect is defined as the direction that a slope or catchment faces (e.g. northeast). Because aspect is a circular measure and ranges from 0 (due north) to 360 degrees (due north) calculation of the mean aspect by hydrologic region using simple averaging techniques was not acceptable. To obtain the mean aspect for each hydrologic region the area weighted average for each catchment was analyzed as a circular distribution (Zar, 1999). To examine the distribution (e.g. variance) of aspects in a given region the angular deviation (s) was used, which is equivalent to the standard deviation on a linear scale (Zar, 1999). Values of s can range from 0 to 81.03, indicating no dispersion or total dispersion around ordinal directions respectively.

Slope

Catchments with higher slopes and hydraulic gradients have increased potential for erosion of soils and movement of coarser textured materials from fluvial transport processes. For example, catchments with steep slopes are found to contribute large amounts of coarse textured materials more efficiently than catchments with lower slope which are found to have a greater proportion of fine textured materials and lower channel gradients (Strahler, 1964). Catchment slope was calculated as area weighted mean values in degrees. The slope of a catchment reflects the rate of change in elevation with respect to area and is an important parameter closely related to measures of catchment relief and hydraulic gradients (Gordon, 2006).

Catchment relief

Catchment relief was calculated as the maximum catchment elevation subtracted by the minimum catchment elevation at the hydrometric gauging station and is related to hydraulic gradients controlling streamflow. Similar to slope, relief indicates the potential energy of a catchment. Catchments with high relief tend to have higher stream gradients and steeper valley slopes; whereas catchments with lower relief have more subdued gradients and lower valley slopes (Strahler, 1958).

Elevation relief ratio

Elevation relief ratio (E) is a dimensionless number that describes the relative proportion of lowland to upland within a catchment is defined by (Wood and Snell, 1960);

Equation 3-1

$$E = \frac{\bar{X}\ Elevation - Minimum\ \ Elevation}{Maximum\ Elevation - Minimum\ Elevation}$$

Defined by mean elevation minus minimum elevation divided by catchment relief; E is equivalent to the more computationally intensive hypsometric integral originally defined by Strahler (1952) but requires much less effort to obtain mathematically (Pike and Wilson, 1971). Low values of E are found in catchments characterized by isolated features of higher relief with greater proportions of flat surfaces; whereas higher values of E tend to be broader catchments of low relief with occasional depressions (Pike and Wilson, 1971).

Topographic variation ratios

Topographic variation ratio 1 (TRV1) is defined as the variance in elevation within a catchment divided by its mean elevation. This ratio describes the general variability in topographic relief within a catchment, which is related to the mean steepness or strength of hydraulic gradients driving runoff processes within a catchment. Runoff should be positively correlated with high TRV1 ratios.

Equation 3-2

$$TVR1 = \frac{S^2\ Elevation}{\bar{X}\ Elevation}$$

Topographic variation ratio 2 (TVR2) is defined as the variance in elevation within a catchment divided by the relief. This ratio is closely related to TRV1 but the denominator is scaled to total relief instead of mean elevation.

Equation 3-3

$$TVR2 = \frac{S^2\ Elevation}{Maximum\ Elevation - Minimum\ Elavation}$$

Solar radiation

Solar energy is important as it drives the hydrologic cycle by controlling evaporation, transpiration and snowmelt processes (Brooks et al., 2003). Solar radiation (both direct and diffuse) can be used to interpret the amount of energy gained by a catchment with larger values being representative of areas with high energy gain. Theoretically, snow dominated catchments with higher energy gain should contribute melt water more rapidly to streams than lower energy catchments. The solar radiation tool in ArcMap Version 9.2. (ESRI 2006, Environmental Systems Research Institute, Redlands, California) estimates solar radiation by calculating a hemispherical viewshed of the sky based on topography (the DEM) and subsequently uses the derived viewshed to estimate direct and diffuse solar radiation from unobstructed sky directions. This process is repeated for every each DEM cell to produce a regional map of estimated solar radiation (ESRI, 2006). This spatial analysis computation integrates the dominant controls over incident solar radiation such as latitude, elevation, slope, aspect, seasonality and shadows. Annual mean solar radiation, in units of Watt hours per square meter (WH/m^2), was calculated spatially at a grid cell size of 150 meters using ArcMap Version 9.2. (ESRI. 2006. Environmental Systems Research Institute, Redlands, California).

3.2.3 Land cover characteristics

Land cover can have significant effects on hydrology. For example, presence of permanent snow or glaciers in a catchment will extend snowmelt peaks and increase baseflows late into the year. The proportion of wetlands might influence regional hydrologic variability by modifying the hydrologic connectivity of catchments by de-synchronizing streamflows through the storage and release of water not being coupled to climatic events. To identify the dominant vegetation and cover types thought to be influential in controlling hydrologic response, spatial land cover data was analysed and compared between hydrologic regions. By identifying differences in the proportion of specific cover types between regions, a greater understanding of the potential influence that land cover may have on streamflow regimes can be gained.

Spatial land cover data for Alberta was downloaded from the Government of Canada, Canadian Forest Service website (Natural Resources Canada, 2003) (http://www.pfc.cfs.nrcan.gc.ca/monitoring/Saforah/index_e.html). The spatial data consisted of grids at a 25 meter cell size, with each grid coded (identified) for a specific land cover type. Data was collected using remote sensing techniques (LANDSAT) during 2002. For the purposes of this study, historic data was considered sufficiently accurate as the cover types of interest to this study were not expected to change significantly since the time of collection. Cover types of interest consisted of the regional proportions of snow and ice, rock, wetlands, herbs (cropland), and forests. Wetlands were originally stratified into three classes (treed, shrub and herb), but for the purpose of this study all three categories were combined into one general wetland class. Forest cover types were stratified into conifer, deciduous and mixedwood vegetation categories and further sub-divided into dense and open cover types. These forest classes were also summarized into one general category of forested area. Spatial analysis was based on the additive proportion of land cover type that was present within each study catchment for each of the six hydrologic regions.

3.2.4 Statistical techniques

3.2.4.1 Regional comparisons of catchment characteristics

Analysis of variance (ANOVA) was used to explore differences in catchment characteristics between the six hydrologic regions. Variables were assessed for normality and homogeneity of variance by examining quantile and probability plots, followed by quantitative Shapiro-Wilk and Leven's tests. Catchment variables of elevation, relief ratio and solar radiation met assumptions of ANOVA but the remaining 6 variables did not and were subsequently transformed using the natural log (Ln). After transformation, some variables still failed to meet equality of variance assumptions for parametric analysis. To overcome this, more robust tests using the Welch and the Brown-Forsythe statistics were applied as they are more conservative with unequal group sizes and applicable in situations where Levene's test is rejected (Zarr 1999). For catchment characteristics that were found to be significant in ANOVA, Tamhane's T2 post-hoc tests was used to identify differences among specific regions ($\alpha = 0.05$). Tamhane's T2 post-hoc test is best used when the assumption of equal variances does not hold and for groups with unequal sizes (Tamhane, 1979; Zar, 1999).

3.2.4.2 Canonical discriminant analysis

To examine which catchment characteristics or groups of characteristics differed between hydrologic regions and to help visually interpret the separation of hydrologic regions with statistically relevant catchment variables, canonical discriminant analysis (CDA) was used (SAS, 2008). Variables which had the greatest loadings on each significant canonical function were considered to be the most influential at discriminating between hydrologic regions. Canonical discriminant analysis was performed by comparing catchment characteristics of each catchment across the six hydrologic regions. This statistical technique assumes linearity, thus the same variables transformed for ANOVA were used in this analysis.

3.2.4.3 Correlation analysis

The association of significant catchment characteristics with significant hydrologic variables (identified in chapter two), were examined across hydrologic regions. Significant hydrologic variables were defined by having the greatest loadings on each canonical function accounting for most of the variation between hydrologic regions (Table 3-2). The objective of this analysis was to determine how the classification approach based on streamflow variables represented or captured differences in catchment physiography. Correlation analysis using Kendall's Tau (τ) statistic was used to explore the covariance between significant catchment characteristics and significant hydrologic variables. Kendall's Tau is a rank based procedure and works well for data that may be skewed, contain outliers, or have monotonic correlations (linear or non-linear), and is insensitive to transformations (Helsel and Hirsch, 2002). Typically a τ value will be less than those found with other correlation coefficients; for example a Pearson's r of 0.90 indicates strong covariance between variables, whereas the Kendall's Tau value of 0.70 is indicative of a similarly strong relationship between the same variables (Helsel and Hirsch, 2002).

3.2.5 Regional comparisons of land cover characteristics

The broad purpose of land cover analysis in this study was to describe additional factors thought to be influencing the observed variability across hydrologic regions and streamflow regimes. However, because of the broad spatial scale of the analysis and the typically weaker associations of runoff behaviour with differences in land cover compared to that of physiography and hydro-climatic regimes, no statistical tests were used to determine differences between regions and land cover. Analysis was for qualitative (descriptive) purposes only. However, observations can still be made in regards to some dominant, large scale differences in cover types between hydrologic regions determined in chapter two. Differences in land cover may have significant influence on regional hydrologic behaviour for this study as the two dominant land use types are forested and agricultural (green and white land use zones) which have been shown to have different hydrologic response characteristics (Poff, 2006). Land cover types were selected based on their potential to influence hydrologic patterns of streamflow magnitude, timing, duration and frequency. To calculate the regional proportions of land cover, each cover type of interest (snow/ice, rock, wetlands, herb/crop and forest) were summed by hydrologic region. The count of 25 meter grid cells occupied by each cover class was converted to an area based measure (hectares) and the proportion (%) of area occupied by each cover class was calculated. These proportions were then compared between regions to investigate patterns that may be influencing streamflow variability across hydrologic regions.

3.3 Results

3.3.1 Regional analysis of catchment characteristics

Because strong spatial gradients were present in many of the hydrologic variables analyzed in chapter two, it was also expected that spatial gradients would exist in the catchment characteristics hypothesized to be influencing observed differences in streamflow regimes across regions.

3.3.1.1 Analysis of variance of catchment characteristics

Statistical analysis of the nine catchment characteristics showed all variables were significantly different between hydrologic regions at $\alpha = 0.05$ (Table 3-3). The value of the ANOVA F statistic provides an indication of the proportion of variance being explained between regions and is representative of strength of the differences among regions for each variable. Elevation had the largest F-statistic of all variables (e.g. the mean differences were the greatest). Solar radiation, relief and topographic variation had the next largest F values respectively (Table 3-3). Subsequent post-hoc tests using Tamahane's T2 test were applied to determine differences between each catchment characteristic among the six hydrologic regions (Table 3-3). Results of post-hoc tests showed similar regional patterns of physiographic gradients as to what were observed in analysis of hydrologic variables from chapter two. The largest differences were observed among the 3 green zone regions; and subsequently between green zone (forested) and white zone (non-forested) regions. White zone regions were comparatively similar to each other for most catchment characteristics with the exception of elevation and solar radiation. Characteristics of topographic variability (TVR1 and TVR2), maximum relief and mean catchment slope followed a spatial gradient, similar to streamflow magnitudes (chapter two), with the largest values in the western Rockies (regions 6 and 1), declining values in the foothills/Boreal (region 5) and with the smallest values in the white zone regions. The higher elevation green zone regions of 6 and 1 were similar to each other for topographic variability, relief and slope, but differed significantly from region 5. The white zone regions (4, 7 and 8) were not significantly different from each other, but a gradient was present with region 4 catchments having the highest mean slope, relief and topographic variation followed by regions 8 and 7 (Figure 3-3 a, b, c, and d). Mean elevations differed significantly between all three green zone regions with the highest mean elevations in region 6 (2183 meters), followed by regions 1 (1715 meters) and region 4 (1081 meters), in the white zone. Green zone region 5 had a mean elevation of 860 meters but was not significantly different from white zone region 4, or regions 7 and 8 having mean elevations of 753, and 712 meters respectively (Figure 3-4). Solar radiation did not differ between regions 6, 1 and 4 which had the largest mean annual values, nor did it differ between regions 5, 7 and 8 which were characterized by lower solar radiation values (Figure 3-5). Elevation relief ratio (E) was lowest in regions 1, 4, and 6, suggesting these catchments were characterized by isolated features of high relief and larger flat areas; E was larger in regions 5, 8 and 7 describing catchments with extensive areas of lower relief with more subdued gradients (Figure 3-6). All regions contained catchments with broad distributions in size. Region 5 had the largest mean catchment area (614 km^2) followed by region 6 (430 km^2), 8 (402 km^2), 1 (244 km^2), 7

(209 km^2) and 4 (187 km^2) (Figure 3-7). Aspect was analyzed as a circular distribution with mean angles ranging from (170 ^{O}) in region 6 to (129 ^{O}) in region 7 (Figure 3-8). This translates to regional catchment aspects ranging from south to east-south-east. The only significantly different mean aspect between groups was found in region 6 (170 ^{O}); all other regions were similar to each other and ranged from SSE (155^O) to ESE (129^O). The smallest angular deviation (s) was found in region 6 (6.83) with s values for regions 1, 7 and 8 ranging from 17.33 to 23.5; region 4 varied the greatest with an angular deviation of 31.2. All regional aspect values were within a range of 90 ^{O} (SSE to ESE) therefore it was assumed that aspect could be neglected as potentially influencing observed differences in hydrologic response between regions.

3.3.1.2 Canonical discriminant analysis

Canonical discriminant analysis of catchment characteristics by hydrologic region was significant overall with 4 of the 5 canonical structures having significantly different class means. The first canonical structure had an eigenvalue of 3.19 which accounted for over 80 percent of the variance; the second function had an eigenvalue of only 0.37 which accounted for 9 percent of the variance. Although the other 2 functions were significant, eigenvalues were less then 0.2 which together accounted for just over 8 percent of the remaining variance in the model, therefore only the first 2 functions were retained for interpretation (Table 3-4). Variables having the highest loadings of the first pooled canonical structure were elevation, relief and solar radiation; all of which had positive canonical correlations with each other. Elevation had the greatest loading (0.92) indicating it was by far the most influential variable for the first function. Loadings for relief (0.547) slope (0.537) and solar radiation (0.539) were very similar, and thus could be considered as equally influential variables in the first function. The most significant variable in the second function was TVR1; only one variable was chosen to represent this function because of the low eigenvalue (0.37). Plotting of canonical scores for the first and second functions showed the significance of elevation; relief and solar radiation variables in differentiating between hydrologic regions (Figure 3-9).

3.3.1.3 Correlation analysis

Significant catchment characteristics (elevation, relief, solar radiation, slope, and TVR1), found by canonical discriminant analysis (above), were compared with the significant hydrologic variables found in chapter two (Table 3-2). The purpose of this was to investigate patterns of covariance between hydrologic and physiographic variables among hydrologic regions and determine if the classification approach (based on hydrograph shape factor) was representative of differences in both regional physiography and surface water hydrologic behaviour.

Correlations among catchment attributes and hydrologic variables showed several important associations between physical features and hydrologic characteristics of hydrologic regions (Table 3-5). Measures of elevation, relief, solar radiation, slope, and TVR1 all had significant ($\alpha = 0.01$) and positive correlations with measures of streamflow magnitude. Slope, maximum relief, and topographic variation had the highest correlations for hydrologic variables of mean annual streamflows (MAQ) and FDC magnitudes of Q30 and Q40 (flows of larger magnitudes). Elevation was associated with a wider range of high and low streamflow magnitudes (MAQ and FDC magnitudes of Q60 and Q99). Solar radiation was more closely associated with streamflows of lower magnitudes (FDC Q99 and Q50, minimum seasonal low streamflow) and had lower correlations with streamflow variables when compared to other catchment characteristics and. Correlations between variables related to streamflow timing (day of minimum seasonal low streamflow) and frequency (intercept of regional FF regression) were highest for elevation, slope and relief characteristics. The only comparisons that did not show significant relationships were between the number of discrete high flow events and descriptors of relief, slope and topographic variation. The number of discrete high flow events and the day of maximum streamflow had the poorest overall associations with catchment characteristics.

Correlations between catchment characteristics were also evident, which was expected as many are based on topographic measures (DEM). Positive associations were evident between elevation, slope, relief and topographic variation (Table 3-6). Relief ratio (E) was negatively correlated with all catchment characteristics. Likewise, area was also negatively correlated with most catchment characteristics, except for relief and measures of topographic variation (TVR1 and TVR2). Given the strong significance of elevation at contributing to regional differences and the correlations present between the same catchment variables found to be significant in canonical analysis, elevation could be used as an overall predictor of solar radiation, slope and relief characteristics across the entire study area.

3.3.2 Regional analysis of land cover characteristics

To identify dominant cover and vegetation types across hydrologic regions the proportions of area occupied by forests, wetlands, croplands, rock/rubble and snow/ice were calculated for each hydrologic region (Table 3-8). Catchments in region 6 had the highest proportion (8 percent) of land occupied by permanent snow and ice fields (including glaciers) and contained the highest proportion of rock and rubble (33 percent) Region 1 had the second highest amount of rock/rubble and snow and ice at 16.9 and 0.28 percent respectively. Region 5 contained the greatest proportion of area in wetlands covering over 21 percent of study catchments. The white zone regions (4, 8, and 7) contained the greatest proportion of land designated as herbaceous, which included agricultural cropland at 59, 46 and 61 percent respectively. In the green zone, region 1 contained 12 percent of its landbase as herbaceous followed by regions 6 (8 percent) and 5 (6 percent) herbaceous cover. The proportion of forested land was highest in region 5 (62 percent), region 1 (55 percent) and region 8 (34 percent) with regions 6, 4, and 7 having lower proportions of forest cover (32, 25 and 24 percent forest cover), respectively. The remaining proportion of land across the 6 regions was occupied by small amounts of water (lakes), non-vegetated land and shrubs. For the purposes of this study these cover types were placed in category of 'other'. Region 6 had the greatest proportion of land cover classified as 'other' (16 percent) 9 percent of which was classified as shadow cast from high elevation ridges

3.4 Discussion

3.4.1 Influence of physiography and land cover on streamflow regimes

By incorporating measures of physiography and land cover into the post classification analysis, critical information was generated that significantly improved understating of how physical catchment characteristics were influencing streamflow regimes across the six hydrologic regions defined in chapter two. The observed differences in catchment characteristics and land cover types across hydrologic regions are important for helping characterize higher order controls thought to be influencing patterns in streamflow regimes between hydrologic regions. However, because of the scale of this approach, only broad inferences can be made in attempting to relate the physical characteristics of regions to their observed hydrologic variability. Specific catchment scale information regarding internal hydrologic processes could further generate insights into why regions differ in terms of specific physical characteristics and how these characteristics influence hydrologic response (Buttle, 2006). This work has the ability to help generate hypotheses regarding hydrologic processes that are influencing regions at a larger spatial scale, which could be used to further understand associations and interactions between the physical controls thought to be driving the spatial variation in hydrologic regimes across the province of Alberta.

3.4.2 Spatial patterns of catchment characteristics

Because of the high spatial variability in topography that exists across the province of Alberta it is reasonable to expect that there would be pronounced physiographic differences among the 6 hydrologic regions. This was shown to be true, especially between the green and white zone regions. Results of ANOVA and canonical discriminant analysis of the 9 catchment characteristics indicated that elevation was by far the most influential factor contributing to physiographic differences between hydrologic regions. Variables of relief, solar radiation and topographic variation (TVR1) were the next most influential. Although slope was emphasized by canonical discriminant analysis as contributing more to regional differences, it had the lowest (although still significant) F statistic in ANOVA (Table 3-3). Strong spatial gradients were evident with elevation, slope and both topographic variation variables; all having the highest values in green zone regions 6, 1 and 5 followed by lower values in white zone regions 4, 7 and 8. This spatial pattern followed provincial topographic gradients moving from west to east (Figure 3-10). Region 5 was more often similar to the white zone regions (4, 7 and 8) than green zone regions 6 and 1 for variables related to elevation, solar radiation, relief, TVR1, and slope (Figure 3-3 a, b, c, and d). This can be attributed to the spatial extent of region 5 as it covers a large portion of the province ranging from the higher elevation east slopes in the west to the Boreal plain in the east; characterized by some of the lowest elevations and measures of relief in the province. In the central part of the province, catchments in region 4 and several catchments from region 8 were found in areas with moderate elevations and relief, resulting in greater mean elevations, slopes and relief values when compared to region 7 catchments, most of which were in areas with lower elevation and relief. Elevation relief ratios, which indicate the proportion of uplands to lowlands, were lowest in regions 1, 4 and 6. These 3 regions can be characterized by upper headwater elevations having isolated features of high relief with lower parts of the catchment often being flatter. Regions 7, 5 and 8 had the smallest E values respectively suggesting catchments within these regions can generally be described as broadly shaped catchments characterized by lower relief gradients (Figure 3-6). This is also supported by the general patterns observed in topographic variability (TVR1 and TVR2) across regions (Figure 3-3 a, b). Catchment area was very similar across the study area and no clear patterns were observed in regional differences except between regions 1 and 5 and between regions 5 and 7. While area weighted streamflow was used as the basis for all streamflow analysis in this thesis, unit area discharge does not completely normalize hydrologic behaviour among large and small catchments. Thus, this result suggests no bias due to this factor was present in the analysis and likely had no material influence in contributing to regional differences (Figure 3-7). Differences in catchment aspect were observed (Figure 3-8), but were not considered informative because calculations may not have been representative of a catchments potential for solar exposure. For example; if the frequency distribution of aspect in a catchment facing south was plotted it would appear strongly bi-modal (many east facing slope and many west facing slopes) and the number of cells contained in the DEM facing south may be low. This example is dependent on catchment shape, as the distribution of slopes with different aspects will change with different catchment forms, but nevertheless complicates using aspect as an informative variable. Furthermore, comparisons of values between arithmetic and circular distribution calculations of aspect (Zarr, 1999) did not result in large differences between regions (data not shown); this is likely due to the small variation in catchment aspects ranging 108^{o} to 170^{o}. These issues were the primary justification for examining the more direct measure of solar radiation. Differences in solar radiation were surprising in that regions with higher elevations had larger annual mean values (Figure 3-5) and the aspects of these regions were generally the most southerly. This relationship was not as clear in the lower elevation, white zone regions. Region 4 had higher solar radiation, similar to regions 6 and 1, but was not significantly different from any region in regards to aspect.

3.4.3 Spatial patterns of land cover characteristics

Regional characteristics in land cover provided a different perspective into differences between hydrologic regions and the results suggest that land cover data may be an important factor influencing streamflow regimes across Alberta. Regions located within the green zone (5, 1 and 6) had more forested area then white zone regions (7, 4 and 8), which contained a greater proportion of herbaceous/cropland cover (Table 3-8). This is reflective of the land zone designation, one being managed as forestlands and the other primarily managed for agricultural production. Region 6 contained the largest proportion of land covered in glaciers and permanent snow fields; the only other region with snow and ice cover was region 1. This is characteristic of Alberta's highest elevation catchments, some of which contain glaciers that contribute significant amount of melt water throughout the year. The proportion of rock was largest in green zone regions 6 and 1 and is characteristic of high elevation mountain landscapes with little or poorly developed soils; all other regions had little to no rock cover, likely a reflection of more developed soils. Regions with the most wetlands (regions 5, 8 and 7) coincided with areas of lower elevation, relief, slope and topographic variation. The pattern of spatial variability observed in catchment and land cover characteristics was also reflected in a suite of hydrologic variables describing the overall flow regime (observed in chapter two) and a sub-set of hydrologic variables found to account for a large proportion of statistical variation (Table 3-2). Both physical and hydrologic descriptors followed a similar gradient suggesting that, at the scale of this study, differences in streamflow regimes are being driven by variation in climate, topography and land cover.

3.4.4 Relationships of physiography to streamflow regimes

Relating the physical attributes of catchments to hydrologic characteristics has been a long standing objective in hydrology. The strength of finding associations between these characteristics is that relationships can be developed for grouping catchments lacking hydrometric data into hydrologically similar groups based on their physical attributes. This approach is reliant on the assumption that physiography is adequately reflective of hydrologic behaviour. In the present study the purpose of developing associations between streamflow and physical catchment characteristics was to examine whether a classification approach based on hydrograph shape factor co-varied with differences in physiography across study regions. Significant hydrologic and catchment variables, found by canonical discriminant analysis were analyzed using Kendall's Tau correlation coefficient. For every variable, except for comparisons between the number of discrete high flow events and topographic variation, comparisons were highly significant ($P < 0.001$) and positively correlated. This may not be surprising from a statistical standpoint, as selected variables were those that accounted for the most variation, and which were also the most statistically. However, from a hydrologic standpoint, these results reveal a spatial pattern in higher order controls and help to identify relationships between regions in terms of physical catchment characteristics and streamflow regimes. Hydrologic variables related to streamflow magnitudes (MAQ, FDC values of Q30. Q40, Q50, Q60 and Q99, and the minimum seasonal low streamflows) co-varied the greatest with catchment variables of elevation, relief, solar radiation, slope and topographic variation (TVR1) (Table 3-7). These catchment characteristics were also correlated with each other (Table 3-6), specifically elevation, solar radiation, slope, TVR1 and relief. This shows that high elevation regions (6 and 1), which are characterized by higher solar radiation, steeper slopes and greater relief have streamflows of larger magnitudes than regions (5, 4, 7 and 8) which have lower elevation catchments characterized by more gradual relief and slopes. Mean catchment slope had the highest correlation with streamflow magnitudes, although it was the least significant in ANOVA and was lower in overall importance from canonical discriminant analysis. This highlights the importance of relationships between catchment slope and streamflow magnitudes at a provincial scale, but shows that at a regional scale catchment slope is not the most powerful discriminatory variable. Elevation and solar radiation had higher correlations with streamflows of lower magnitudes than high magnitudes. It may be possible that higher elevation catchments are better correlated to low flows (base flows) because at these elevations higher temperatures and summer radiation inputs are melting available snow and ice and contributing to streamflows later in the season, whereas the recession to baseflow conditions in lower elevation catchments has already started.

Streamflow timing variables (day of maximum streamflow, day of half streamflow and day of minimum streamflow) had the highest correlations with elevation, slope and relief. Regions with higher elevations, steeper slopes and greater relief tended to have later timing of streamflows. From a runoff perspective, steeper slopes should result in faster timing of streamflows, but when slopes are associated with higher elevations in a snow dominated system the opposite pattern may be more reasonable to expect. Snowmelt will be occurring later in catchments at higher elevations and providing a greater amount of available water for contributions to snow melt peaks, which are often observed as the day of maximum streamflow in these systems.

Hydrologic variables related to streamflow frequency did not account for a large proportion of variance between regions (7.7 percent) or have an eigenvalue greater than one (data not shown). These variables are, nevertheless, interesting to consider because of common management concerns over peakflows and potential flooding issues. The intercept of the regional flood frequency regression showed positive correlations between all 5 of the significant catchment characteristics; with variables of elevation, slope and relief having the highest correlations. This indicates that the magnitude of high flows for a given return interval within a region will be larger with characteristics of increasing elevation, slope and relief of a region. This was evident by examining regional FF regression lines (data not shown) as regions 6 and 1 had higher FF intercepts relative to other regions. The discrete number of high flow events was the only hydrologic variable that did not have significant association with catchment descriptors of relief, slope or topographic variation. Both elevation and radiation were correlated with the number of high flows, suggesting a greater number of high flow events (on average) occur in regions that have higher elevation and solar energy gain.

3.3.5 Comparison of findings to landscape based approaches

The delineation of hydrologic regions based on hydrograph shape factor did not include any *a priori* assumptions of which specific higher order controls were thought to be influencing streamflow response. However, strong associations were found between catchment characteristics, streamflow magnitudes and the timing of streamflows. These findings, at a large provincial scale, support the idea that a classification framework based on hydrometric data can identify differences in higher order controls at larger scales, although not initially considered in the classification process. The hydrometric approach adequately described differences in physiography, although is perhaps best applied at larger spatial scales or more heterogeneous areas. Conversely, hydrologic classification using a landscape based approach could be considered to reasonably represent broad aspects of streamflow regimes as catchment variables were well correlated with the dominant gradients observed in the magnitude and timing of streamflows. Although the frequency and duration of streamflows were not well captured by physiographic characteristics, these categories of hydrologic variables were not as influential at contributing to major differences in hydrology between the six regions. The hydrologic classification approach produced for Alberta by Golder (2006, *unpublished*) using landscape and climate to infer hydrologic similarity identified strong gradients in topographic and climatic variation and delineated regions along a similar spatial gradient to what was found in this study. However, while Golder (2006, *unpublished*) did identify strong regional gradients of mean annual streamflow magnitudes, they did not perform a thorough analysis of the variation in hydrologic behaviour among their classified regions which would have ultimately provided much greater insight into regional hydrologic differences. Although this study identified fewer hydrologic regions than the Golder (2006, *unpublished*) study, each of the hydrologic regions in the present study was markedly different in regards to its overall streamflow regime and selected physiographic characteristics. The present study supports the notion that streamflow magnitudes are the primary variables that distinguish hydrologic variability across the province, but not necessarily the variable of mean annual streamflow. Furthermore, by using only physiographic variables to classify hydrologic regions in Alberta, the classification results of Golder (2006, *unpublished*) likely do not reflect an optimal description of the actual hydrologic variability across Alberta. Hydrologic variables of high, average and low flows as well as measures of streamflow timing should be accounted for as they co-vary differently with catchment characteristics across the province of Alberta.

The advantage that a streamflow based approach offers over landscape based approaches is that it will identify regions in terms of unique hydrologic response that may be neglected using a physically based approach. Unique hydrograph shapes were evident between regions 6 and 1, as region 6 catchments contained headwater glaciers and in region 1 no glaciers were present; however, these two regions were similar to each other for many of the physical descriptors examined. The presence of glaciers and permanent ice fields are important attributes driving hydrologic differences between these two regions. Another region which may not have been identified if a landscape based approach had been taken is region 4. Region 4 hydrographs were very unique from other regions and analysis of hydrologic variables suggested that this region was influenced to a higher degree by ground water than other regions. However, physical characteristics of this region were often similar to regions 6 and 5 and also with regions 7 and 8; making this region more likely to be missed in an approach based primarily on physical characteristics.

Another potential issue with starting from a landscape perspective is the selection of relevant catchment variables that are representative of the study area. Because there is no physical variable that represents all higher order controls; selection of physical variables for classification is difficult and may introduce undesired biases into classification results. It is important to note that this problem is also present with approaches based on hydrologic variables (Olden and Poff, 2003). However, in this study, the issue of variable selection was avoided by selecting the shape factor of the hydrograph as a “parsimonious” or “master” variable by which most components of the streamflow regime (magnitude, timing, frequency and duration of streamflows) were represented during the classification process.

A hierarchal and landscape based model for hydrologic classification, such as that of Devito *et al.* (2005) argues that the higher order controls of climate, bedrock geology, surficial geology, soils, and topography should be considered in descending scale of importance, respectively. Obviously climate is the dominant driver of hydrologic behaviour across Alberta, but interactions are not implicitly considered under this conceptual framework. The hierarchy of controls is most likely different for catchments located in the western part of the province (Rocky Mountains) than for catchments located in the eastern part (Boreal plain). Furthermore, it is possible that a transitional zone between individual controls driving hydrologic behaviour is present across the province. Devito *et al.* (2005) argue that topography should be considered last in a classification framework, as water often flows between topographic divides. However at a provincial scale, the present study shows that topography is one of the more influential controls determining regional hydrologic differences. At finer spatial scales and in areas of low relief, such as the Boreal plain of Alberta (region 5), the influence of geology and soils may exert a greater role then topography in influencing catchment hydrology and streamflow. A more applicable approach for determining the role of catchment controls on streamflow would be the T^3 template of Buttle (2006). This approach assumes catchments (or regions) being considered are within the same hydro-climatic setting (which this study has identified) and ‘maps’ them according to differences in topology, typology and topography. Topology is reflective of the role of hydrologic connectivity present in influencing hydrologic response, topography is describe by hydraulic gradients controlling streamflow response and typology is characterized by the relative differences between vertical and lateral hydrologic pathways (Buttle, 2006). By examining each hydrologic region in this framework, this study has identified the dominant controls that may be influencing the observed hydrologic differences between regions. However, while the approach used in this study captured the streamflow “signal” stemming from the interaction of controls, it still lacks the ability to answer the question of which catchment characteristics offer the strongest universal explanation of streamflow response. In fact any landscape based framework or approach will never truly be reflective of all streamflow regimes because landscape controls are considered first and hydrologic response second.

3.5 Conclusion

The six hydrologic regions delineated in chapter two showed clear differences in terms of streamflow regimes, hydrograph shapes, and individual streamflow characteristics. The present study (chapter Three) clearly identified regional differences in physiography and patterns of vegetation and land cover between defined hydrologic regions. When selecting between a landscape or streamflow based classification approach, the intent of classification needs to be carefully considered. Landscape based approaches are often necessary due to the scarcity of adequate hydrometric records or are sometimes combined with hydrometric data to predict (model) streamflows in ungauged catchment (PUB, Sivapalan *et al.*, 2003). Streamflow based approaches have been used for relating hydrologic variability with macroinvertebrate communities (Monk, 2008; 2006), to asses hydrologic change from development (e.g. dams) (Richter, 1996) and for ecologically based in-stream flow needs assessments (Kennard *et al.*, 2010). By using both streamflow and physiography the ideology of each approach can be captured and insights into the influence and interaction of higher order controls across the province of Alberta and their influence in modifying streamflow regimes were captured.

Table 3-1 Catchment characteristics used to compare the spatial differences in physiography across the six hydrologic regions.

Variable	Units/ Abbreviation	Definition
Catchment Area	Square kilometers (Km^2)	Gross watershed area above gauging location
Elevation	Meters (MASL)	Mean catchment elevation
Aspect	Degrees (º)	Area weighted catchment orientation
Slope	Degrees (º)	Area weighted mean catchment slope
Relief	Meters (MASL)	Maximum elevation subtracted by the minimum elevation of the catchment
Elevation Relief Ratio (E)	Dimensionless	Mean elevation minus minimum elevation divided by relief
Topographic variation Ratio 1 (TVR1)	Dimensionless	Variance in elevation within a catchment divided by the mean elevation
Topographic Variation Ratio 2 (TVR2)	Dimensionless	Variance in elevation within a catchment divided by the relief
Solar Radiation	Watt hours per square meter (WH/m^2)	Area weighted mean annual shortwave radiation

Table 3-2 Hydrologic variables from Chapter Two found to be significant using canonical discriminant analyses. Variable were used in correlation analysis with selected catchment characteristics (Table 3-1). The order of variables for each function indicates the relative importance (axis loading) within that function. The proportion of variance explained for each function is denoted in brackets.

Canonical Function 1 (70.7%)	**Abbreviation and Units**
Mean minimum seasonal low streamflow	QminSLF (mm/day)
Day of half of mean annual streamflow	Half_FlwDt (Julian day)
Mean streamflow at the 40th percentile of the FDC	FDC Q40 (mm/day)
Mean streamflow at the 50th percentile of the FDC	FDC Q50 (mm/day)
Day of mean maximum streamflow	Dmax (Julian day)
Mean streamflow at the 30th percentile of the FDC	FDC Q30 (mm/day)
Mean streamflow at the 60th percentile of the FDC	FDC Q60 (mm/day)
Mean annual streamflow	MAQ (mm/year)
Canonical Function 2 (14.4%)	
Day of minimum mean seasonal low streamflow	DminSLF (Julian day)
Day of mean maximum streamflow	Dmax (Julian day)
Streamflow at the 99th percentile of the FDC	FDC Q99 (mm/day)
Canonical Function 3 (7.7%)	
Mean intercept of the regional flood frequency regression	FF_int
Mean number of discrete high flow events	NmbHF

Table 3-3 ANOVA and post-hoc test comparison results of differences between hydrologic regions and catchment characteristics ($\alpha = 0.05$). Letters denote statistical significance between regions for post-hoc test comparisons.

				Post-hoc tests					
Variable	**F-stat**	**d.f.**	**p value**	**Region 6**	**Region 1**	**Region 5**	**Region 8**	**Region 7**	**Region 4**
Elevation	108.24	210	< 0.001	a	b	c	c	c	abc
Solar Radiation	40.24	209	< 0.001	a	a	b	b	b	a
Relief	37.73	210	< 0.001	a	a	b	c	c	bc
TVR2	36.36	210	< 0.001	a	a	b	c	c	bc
TVR1	25.50	210	< 0.001	a	a	b	c	c	bc
Aspect	11.33	210	< 0.001	a	b	bc	c	cd	abcd
Catchment Area	6.05	210	< 0.001	ab	a	b	ab	ab	ab
Elevation Relief Ratio	4.60	210	0.001	ab	a	b	b	b	ab
Slope	4.04	210	< 0.001	a	a	b	c	c	bc

Table 3-4 Canonical structures for the first 2 canonical functions representing correlations between catchment characteristics. The percent variance explained by each function is listed at the bottom. Variables are in order of relative importance (e.g. function loading) with (+) denoting positive correlations between individual variables within each function.

Canonical Function 1	Canonical Function 2
(+) Elevation	(+) TVR1
(+) Relief	
(+) Solar Radiation / Slope	
Variance explained (%)	
80.2	9.4

Table 3-5 Kendall's Tau (τ) correlation coefficients between significant hydrologic variable from chapter 2 and catchment characteristics. Hydrologic variables are in order of significance (axis loading) from canonical discriminant analysis. Catchment characteristics are in similar order. Catchment variables of area, aspect, r_ratio and TVR2 are not shown.

	ELEVATION	RELIEF	RADIATION	SLOPE	TVR1	AREA	ASPECT	R_RATIO	TVR2
QminSLF	.581**	.550**	.446**	.561**	.477**	0.003	.366**	-0.090	.522**
Half_FlwDt	.415**	.419**	.335**	.407**	.376**	0.077	.289**	-0.039	.396**
FD_0_4	.575**	.554**	.428**	.596**	.492**	-0.048	.412**	-0.088	.543**
FD_0_5	.582**	.549**	.442**	.584**	.480**	-0.051	.400**	-0.091	.532**
Dmax	.321**	.364**	.261**	.353**	.336**	.107*	.299**	0.001	.344**
FD_0_3	.572**	.559**	.422**	.611**	.501**	-0.046	.420**	-0.088	.554**
FD_0_6	.587**	.537**	.453**	.567**	.463**	-0.058	.390**	-0.089	.515**
MAQ	.587**	.566**	.441**	.607**	.501**	-0.016	.427**	-0.087	.555**
DminSLF	.497**	.458**	.378**	.494**	.400**	0.002	.285**	-.140**	.437**
FD_0_99	.586**	.452**	.485**	.490**	.364**	-.136**	.357**	-0.088	.406**
FF_int	.481**	.435**	.347**	.473**	.392**	-0.049	.370**	-0.040	.449**
NmbHF	.165**	0.080	.158**	0.038	0.059	-0.015	.117*	0.034	.097*

**. Correlation is significant at the 0.01 level
*. Correlation is significant at the 0.05 level

Table 3-6 Kendall's Tau (τ) correlation coefficients between all catchment characteristics. Shaded values denote variables having the highest correlations between each other.

	AREA	ASPECT	SLOPE	RELIEF	ELEVATION	R_RATIO	TVR1	TVR2	RADIATION
AREA	1.000								
ASPECT	-0.050	1.000							
SLOPE	-0.086	.482**	1.000						
RELIEF	.184**	.380**	.662**	1.000					
ELEVATION	-.123**	.383**	**.719****	.520**	1.000				
R_RATIO	-.100*	-0.006	-.170**	-.286**	-.134**	1.000			
TVR1	.207**	.352**	.578**	**.828****	.404**	-.255**	1.000		
TVR2	.115*	.372**	.650**	**.782****	.495**	-.206**	**.858****	1.000	
RADIATION	-.154**	.245**	.526**	.391**	**.781****	-.165**	.267**	.344**	1.000

**. Correlation is significant at the 0.01 level

*. Correlation is significant at the 0.05 level

Table 3-7 Kendall's Tau (τ) correlation coefficients between hydrologic and basin characteristics found significant using canonical discriminate analysis. Light grey shaded values, bolded light shaded values and bolded dark shaded values denote higher correlation coefficients, respectively.

Flow Group		ELEVATION	RELIEF	RADIATION	SLOPE	TVR1
Magnitude	MAQ	**.587****	**.566****	.441**	**.607****	**.501****
	FDC Q30	.572**	**.559****	.422**	**.611****	**.501****
	FDC Q40	.575**	**.554****	.428**	**.596****	**.492****
	FDC Q50	.582**	.549**	**.442****	.584**	.480**
	FDC Q60	**.587****	.537**	.453**	.567**	.463**
	QminSLF	.581**	.550**	**.446****	.561**	.477**
	FDC Q99	**.586****	.452**	**.485****	.490**	.364**
Timing	Dmax	.321**	.364**	.261**	.353**	.336**
	Half_FlwDt	.415**	.419**	.335**	.407**	.376**
	DminSLF	.497**	.458**	.378**	.494**	.400**
Frequency	NmbHF	.165**	0.080	.158**	0.038	0.059
	FF_int	.481**	.435**	.347**	.473**	.392**

**. Correlation is significant at the 0.01 level

*. Correlation is significant at the 0.05 level

Table 3-8 Proportion of land cover types by hydrologic region. Bold and dark grey shaded values denote regions having the largest proportions by land cover type; light grey shaded values are regions having the second largest proportion of land cover between regions.

Hydrologic Region	Forest	Wetlands	Crop/Herb	Rock/Rubble	Snow/Ice	Other
Glacial (6)	32.8	0.6	8.3	**33.7**	**8.4**	**16.3**
Rockies (1)	55.5	2.9	12.9	16.9	0.3	11.5
Foothills/Boreal (5)	**62.8**	**21.2**	6.9	0.1	0.0	9.1
W.Z. Inner (8)	34.9	13.3	46.0	0.0	0.0	5.8
W.Z. Outer (7)	24.8	8.1	**61.4**	0.0	0.0	5.6
W/Z Central (4)	25.4	7.0	**59.8**	0.8	0.0	7.1

Figure 3-1 Map of Alberta showing six hydrologic regions obtained from hierarchical cluster analysis of hydrograph shape variables and 4 study landbase zones; (1) green zone (forested landbase), (2) white zone (agricultural landbase), (3) 80km buffer surrounding the green zone, and (4) 100km buffer around the province.

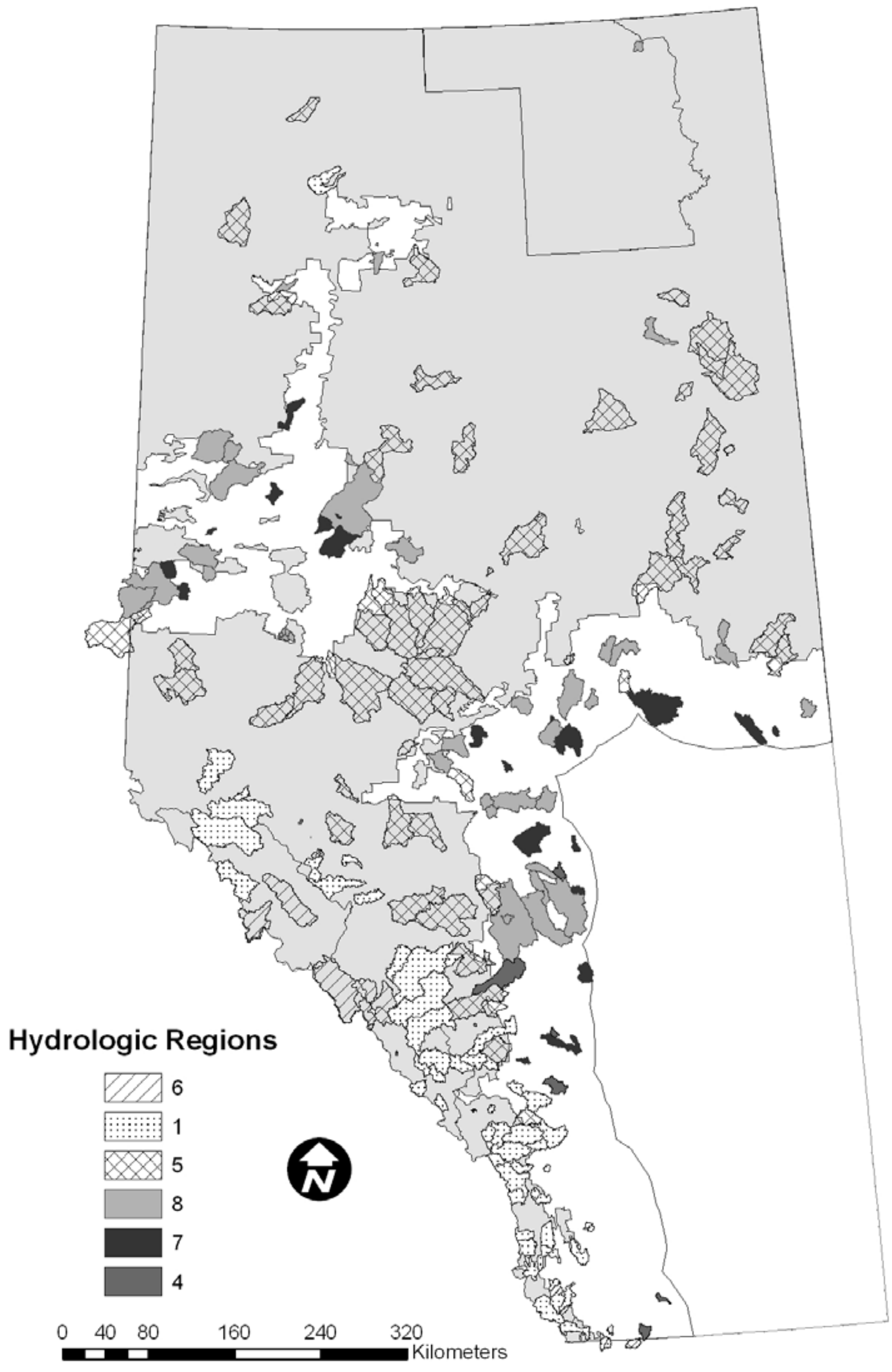


Figure 3-2 Hydrographs grouped by final cluster membership showing averaged cumulative streamflows (mm) over 21 day periods for the six hydrologic regions.

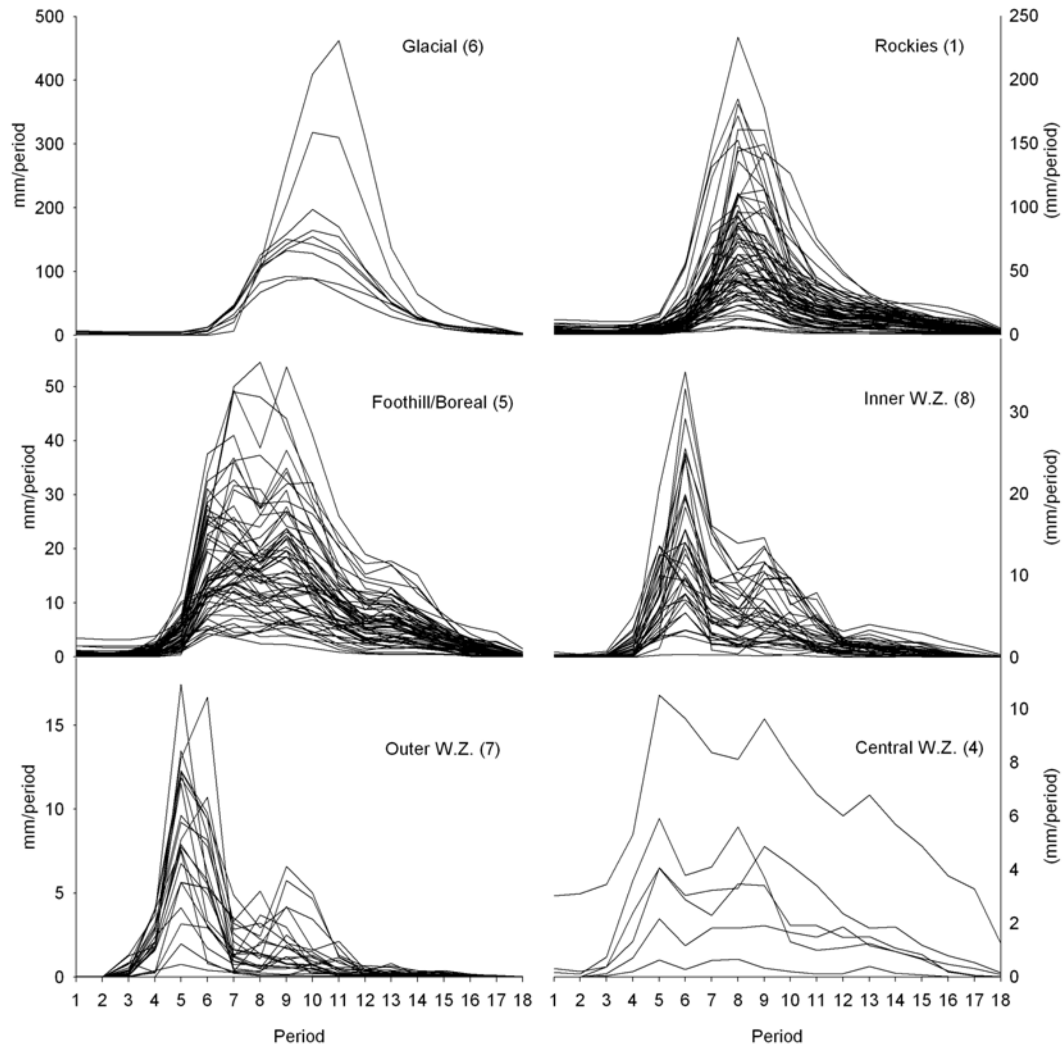
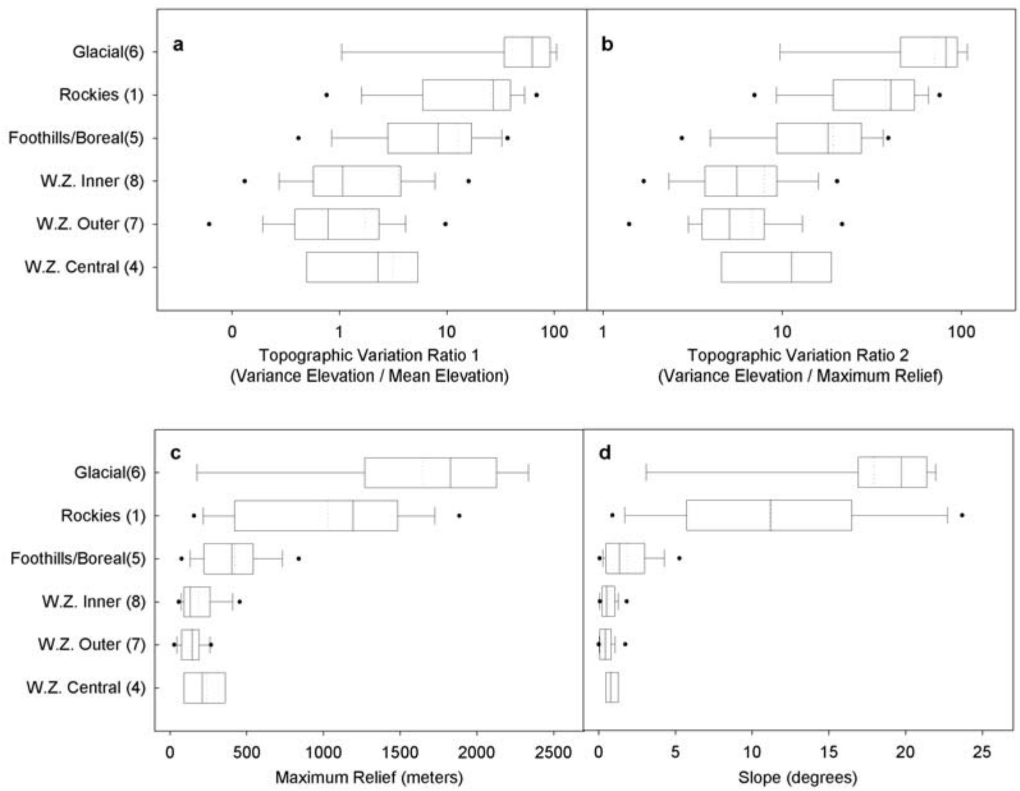
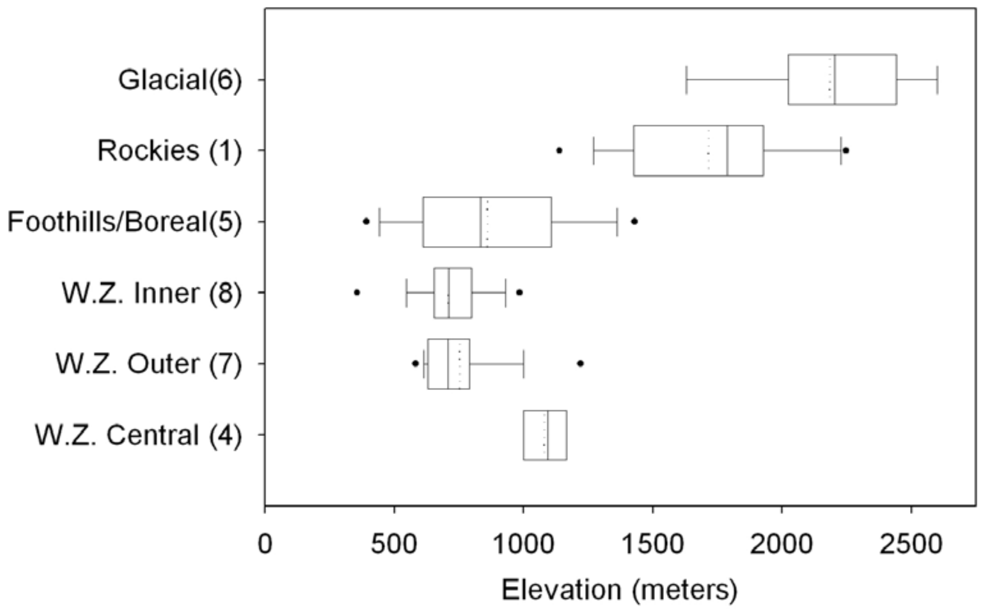


Figure 3-3 Box plots[11] of catchment characteristics showing regionally similar trends for variables of topographic variation ratio 1 (a) and 2 (b), (c) maximum relief and (d) mean catchment slope. Note: Topographic variation ratio 1 (a) and 2 (b) are plotted on a log scale.



[11] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-4 Box plot[12] of catchment elevations by hydrologic region.



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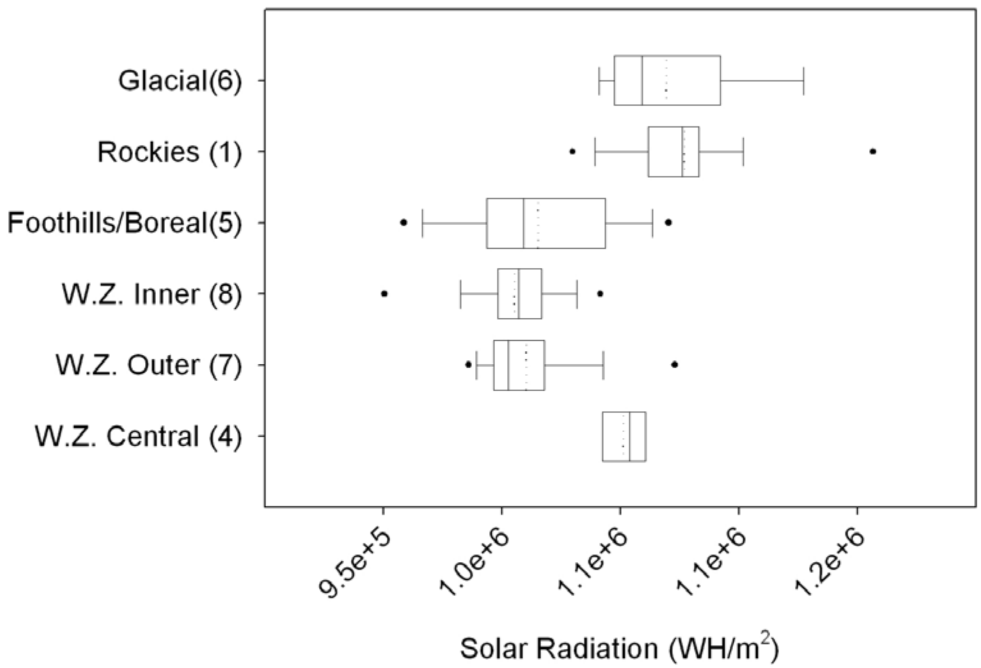
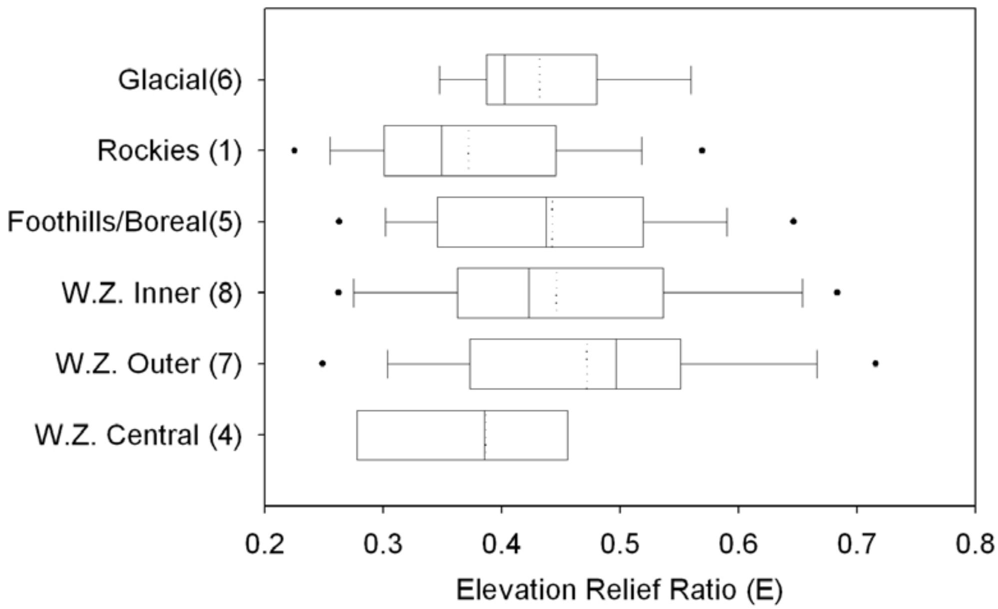
[12] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-5 Box plot[13] of spatially estimated mean annual solar radiation (WH/m^2) by hydrologic region.



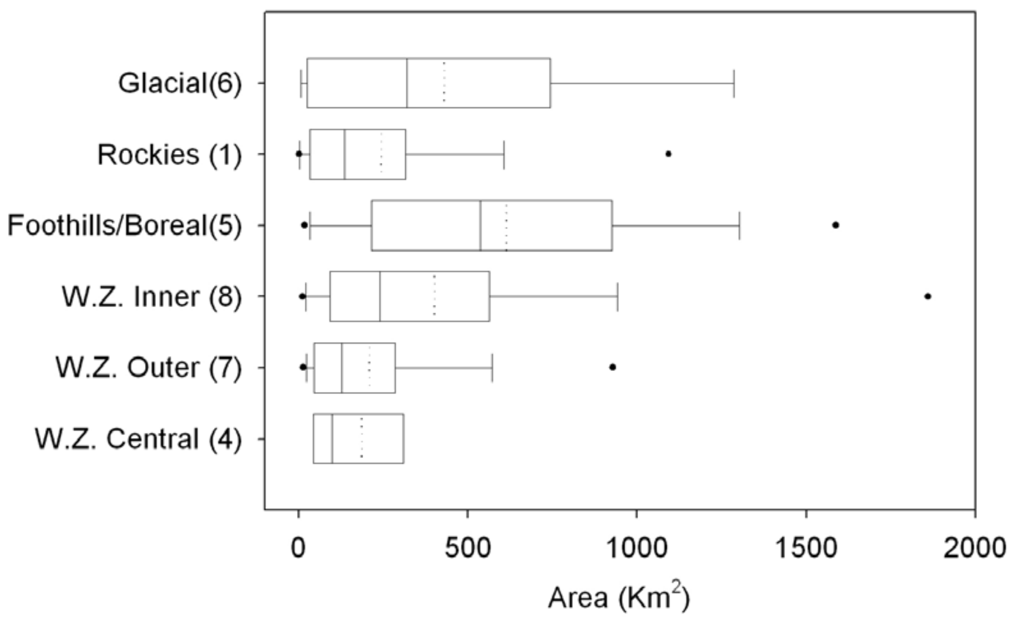
[13] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-6 Box plot[14] of catchment elevation relief ratios (E) by hydrologic region.



[14] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-7 Box plot[15] of catchment area (Km^2) by hydrologic region.



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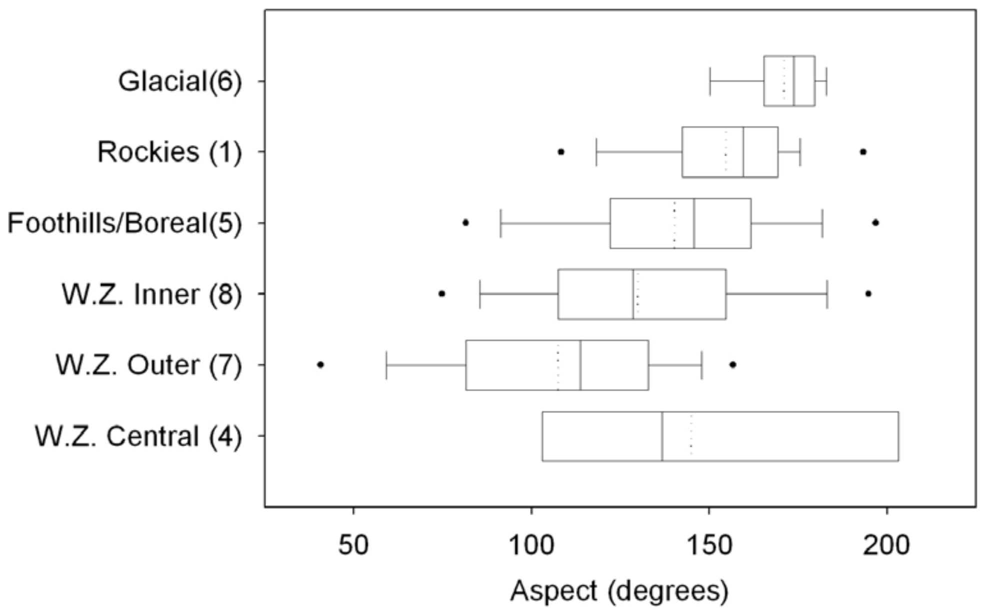
[15] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-8 Box plot[16] of catchment aspect by hydrologic region.



[16] Box plots describe the dispersion of the data around the mean and median. The middle solid line indicates the median value; the dotted line represents the mean. Outer edges of the box are the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outer dots (if present) indicate the 5th and the 95th percentiles.

Figure 3-9 Canonical scores of catchment characteristics for the first and second canonical functions showing the separation between hydrologic regions in multivariate space. Variables listed on each axis are those accounting for most of the variance of that function.

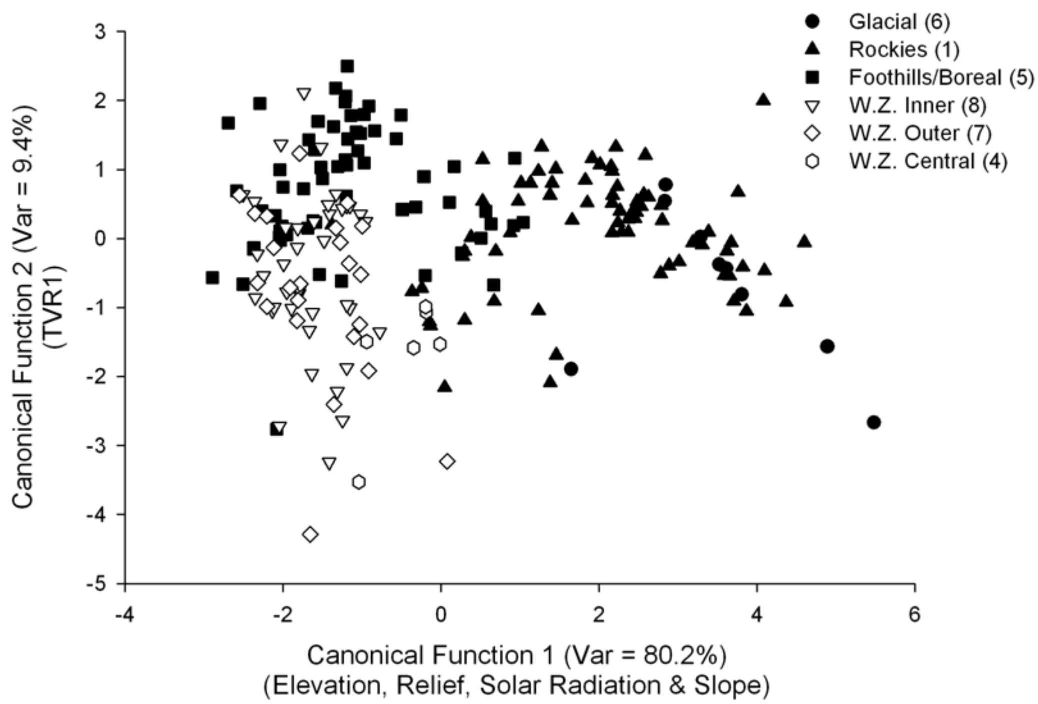
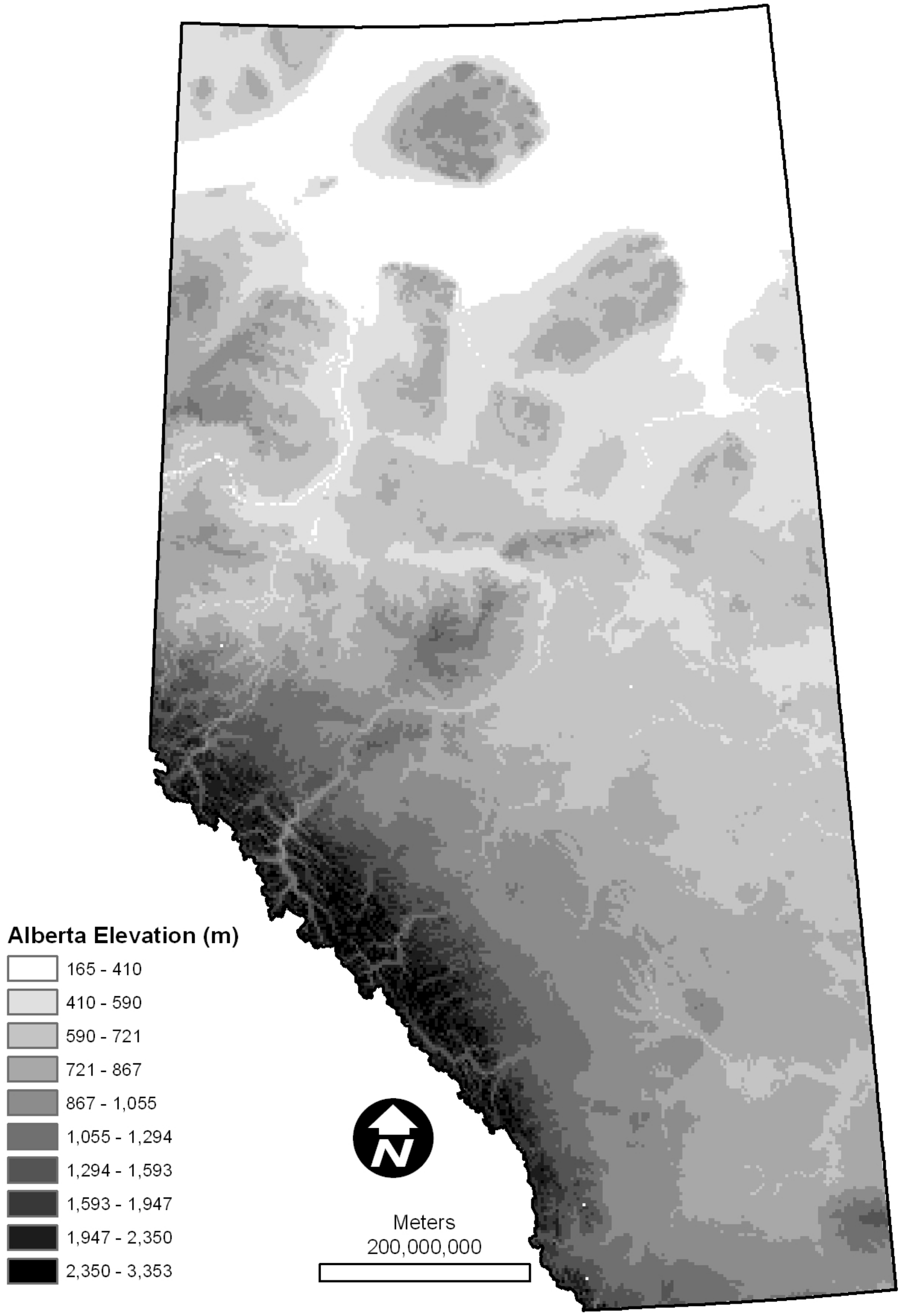


Figure 3-10 Digital elevation model of Alberta showing the topographic gradient from high (south-west) to low (north-east).



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Chapter 4: Hydrologic Risk Assessment Framework

4.1 Introduction

The effects of forestry activities (harvesting, site preparation and road networks) on the hydrology of forested landscapes principally results from the alteration of interception and evapotranspirational processes of the forest canopy (Brown *et al.*, 2005; Stanley and Arp, 2002). The impacts of timber harvesting on hydrological processes are often observed through increased streamflows (Bosch and Hewlett, 1982; Hornbeck *et al.*, 1993; Stednick, 1996), altered timing of streamflows (Hetherington, 1982; Hornbeck, 1975; Swank *et al.*, 2001) and changes to water quality (Bormann *et al.*, 1968; Krause, 1982). However, the magnitude of hydrologic change associated with forest harvesting treatments can be generalized as 'highly variable' (Hibbert, 1967) and is dependent on the physical structure and climatic setting of the catchment combined as well as the severity and extent of disturbance. The effects of forest disturbance on hydrology are not static and, as the forest regenerates, effects diminish over time with the recovery of interception and evapotranspirational processes. Quantification of the hydrologic impacts from forestry activities has been evaluated using hydrologic models that forecast changes to hydrology (e.g. water yields) and to predict the hydrologic recovery of forests to pre-disturbance conditions. These approaches are typically applied over times scales that approximate forestry rotation periods (e.g. 100 years).

Several barriers exist that prevent the successful integration of watershed and hydrologic issues into the forest management planning process. One of the central issues in the evaluation of forest management plans in Alberta (and Canada) is the lack of scientifically defensible thresholds or benchmarks to assess acceptable levels of change in hydrologic behaviour of a watershed or region that can occur. Appropriate hydrologic thresholds have not been established, explored or tested using valid scientific methods. Even in the case where defining an acceptable threshold is ambiguous, (which is often the case with defining hydrologic criteria and indicators [CCFM, 2006]) the definition of other benchmarks commonly used in ecosystem management such as the natural range of variability (NRV) have not yet been explored. This creates enormous difficulties for both forest managers and regulators, who often rely on forest hydrologists to evaluate the sensitivity of a watershed to disturbance. Another central barrier is the expertise required to interpret climatic and hydrologic datasets, which creates difficulties in evaluating model output and relating results to what is actually occurring during forestry operations. Although these models were intended to be routinely applied by forest managers, the interpretation is often outside the expertise of typical forest planning teams. Lastly and perhaps the most important challenge is hydrologic variability. Regional hydrologic characteristics are extremely variable, both spatially and temporally (McDonnell and Woods, 2004). This hydrologic variability is especially pronounced across Alberta's forested regions from the northern Rocky Mountains, to the upper and lower foothills, and throughout the Boreal plain. This variability makes defining forest management benchmarks and thresholds in the province difficult, if not impossible due to lack of basic hydrologic information.

Several key issues need to be addressed to increase the forest manager's ability to evaluate and integrate watershed concerns into the forest management planning process. (1) The hydrologic variability across Alberta needs to be described and grouped into regions characterized by having similar hydrologic characteristics, (2) regionally specific hydrologic criteria and indicators need to be explored and/or defined using hydrologic thresholds (if present) or by incorporating a NRV management based approach, and (3) current hydrologic models that simulate changes in mean annual streamflows could to be adapted to incorporate the hydrologic threshold or the natural range of hydrologic variation within a region. In chapter one, the province of Alberta was classified into hydrologically homogeneous regions and the dominant sources of hydrologic variability were identified. This work identified potential hydrologic criteria and indicators at a coarse scale. However, these hydrologic parameters were not linked to current forest management planning tools to enable linkages between the changes of annual streamflows to additional hydrologic parameters likely important to society and the environment. To link current forest management planning model outputs of projected changes to annual water yield and hydrologic parameters of interest, several assumptions are necessary. (1) The regional temporal variation in annual streamflows is representative of the regional temporal variation in climate (e.g. years having higher annual streamflows are representative of years with higher annual precipitation), (2) forest disturbance (harvesting) generally increases the amount of water available for generation of runoff, and (3) within a hydrologic region, watersheds with lower annual streamflows represent dryer conditions (e.g. unharvested watersheds) and watersheds with higher streamflows represent wetter conditions (e.g. harvested watersheds [see assumption 1]). These three assumptions allow the development of relationships between current forest management planning model outputs (changes to annual streamflows) and hydrologic parameters of interest. This research will allow for the evaluation, demonstrated by a forest management case study, of regional hydrologic thresholds across the forested landbase of Alberta and development of a scientifically defensible framework that integrates watershed concerns into the forest management planning process for hydrologic parameters other than annual streamflows.

4.1.2 Objectives

The broad objectives of this study were to identify hydrologic thresholds for a subset of hydrologic variables considered important from an ecological, societal and water resource management perspective in each region (if they exist) or define the natural range of hydrologic variation (NRV) for a this same subset of hydrologic variables and to determine how disturbance (e.g. forest harvest) impacted the magnitude, timing, frequency and duration of streamflows. More specifically, the objectives of this study were to (1) identify a sub-set of hydrologic variables that are sensitive to and that co-vary with gradients in mean annual streamflow (which is assumed to be driven by climatic variability), (2) examine regional streamflow relationships for presence of hydrologic threshold (if they exist) or define the NRV of hydrologic variables that co-vary with gradients in mean annual streamflow, (3) examine regional differences in the NRV of hydrologic variables to determine if regionally specific hydrologic criteria and indicators should be developed and, (4) incorporate these findings into an integrated forest planning risk assessment framework, illustrated using a case study, to explore how potential hydrologic thresholds or NRV might be used to evaluate projected impacts of forest management scenarios across hydrologic regions. The findings of this study will provide guidance for evaluating hydrologic change as a result of planned forest management activities and will be used to explore the hydrologic impacts associated with forest harvesting based on a risk assessment framework for the province of Alberta.

4.2 Methods

4.2.1 Selection and calculation of hydrologic variables

In chapter two, 36 hydrologic variables were selected based on hypothesised sensitivity to change from natural or anthropogenic disturbance and from past research guiding the selection of hydro-ecological indices representative of streamflow regimes (Richter *et al.*, 1996; Olden and Poff, 2003). Analysis of these variables revealed a sub-set of nine hydrologic variables that captured the majority of the hydrologic variation between 6 hydrologic regions that were delineated based on the standardized mean annual hydrograph shape (Figure 4-1). These nine hydrologic variables represented measures of streamflow magnitude (mean, maximum and minimum annual streamflows) and timing (dates of maximum and minimum annual streamflows). These findings suggested that measures of streamflow magnitude and timing account for the majority of the observed differences in hydrology across the province of Alberta. For the present study, the original 36 hydrologic variables were re-evaluated in the context of their relationship to regional gradients in the temporal variation of climate. Assessing the climatic sensitivity of hydrologic variables was used to explore how variables related to gradients from wetter to dryer climatic conditions. The assessment of climatic sensitivity was accomplished by using the temporal variation in regional annual streamflows as a surrogate for the temporal climatic gradients between wet and dry years. This assumes that regional temporal gradients in annual streamflows within a hydrologically homogeneous region (e.g. watersheds with high and low annual water yields) are representative of regional climatic variability (e.g. wet to dry years). The regional relationships between hydrologic variables and annual water yields served as a proxy for exploring the impact of forest disturbance on hydrology at a regional scale under the assumption that forest harvesting generally increases water production within a catchment.

To select representative hydrologic variables for this study, annual values for each of the 36 hydrologic variables were plotted against annual streamflows for the period of record (number of years) in each study watershed, by hydrologic region. Variables showing regional temporal trends with annual streamflows (representing regional temporal variability in climatic gradients) were retained. These hydrologic variables were subsequently examined for correlations to determine variables that were representative of one another (e.g. redundant) to reduce the final number of variables. Due to the large number of data points for each comparison (hydrometric station years within watersheds within regions) mean values were used for each watershed. This averaging technique resulted in substitution of the inter-annual hydrologic variability for spatial variability within a hydrologic region (e.g. space for time). Thus, within a hydrologic region, the range of hydro-climatic conditions across study watersheds was considered representative of the regional hydrologic NRV. The final subset of 8 hydrologic indices were broadly representative of the overall streamflow regime and included variables describing the magnitudes of high and low streamflows, the timing of high and average streamflows and the frequency and duration of both high and low streamflows (Table 4-1). To determine if relationships between selected hydrologic variables and climatic gradients (mean annual streamflows) were statistically significant, conventional linear regression was applied for each variable by region using the average values for each watershed at a significance level of $\alpha = 0.05$ (SAS Version 9.2, SAS institute Inc., Carey, North Carolina).

4.2.2 Defining hydrologic thresholds

To examine the presence of thresholds between regional hydrologic variables and mean annual regional streamflows individual regression relationships were evaluated visually for any indication that suggested evidence of a change in relationships as mean annual regional streamflow increased. A threshold was defined as (1) any relationship that showed a non-linear trend as mean annual regional streamflows increased, (2) a negative intercept, and (3) evidence, through the visual evaluation of data points distribution, that indicated two separate relationships may be present. Examination of the relationships of each hydrologic variable with variation in annual water yield within regions did not indicate the presence of any clearly definable hydrologic thresholds, and thus, the regional natural range of hydrologic variability (NRV) was used as a coarse management threshold for this study. Describing the natural range of variation (NRV) of an ecosystem is a practical starting point to assess historic fluctuations in environmental conditions and can provide scientists and managers a starting point in which to quantify ecosystem alteration from management activities (Morgen *et al.*, 1994). Managing for the NRV is often practiced in ecosystem management for the reason that realizing the consequences of anthropogenic changes to the environment is not truly possible; however, if the natural range of variability is approximated (for example, by managing forest structure or health) the environmental conditions to which species are adapted to will be maintained (Landres *et al.*, 1999)

Approaches based on managing for the NRV of water resources and fluvial systems have also been applied in hydro-ecological contexts. Richter *et al.* (1997) proposed using ecological based NRV concepts for quantifying streamflow-based management targets to sustain the ecologic integrity and biodiversity of aquatic ecosystems. Defining the hydrologic NRV is commonly accomplished using +/- 1 standard deviation from the mean (e.g. 68% confidence interval) (Richter *et al.*, 1996; Richter *et al.*, 1997); although many other approaches have been used to define the hydrologic NRV. Sanford *et al.* (2007) defined the inter-annual variability of streamflows using a measure of dispersion around the median defined by the 90th percentile - 10th percentile / 50th percentile. The coefficient of variation (standard deviation / average) has also been applied to describe the NRV of ecologically important hydrologic variables (Poff and Ward, 1989). The above examples illustrate that concepts of the natural range of hydrologic variability have not been rigorously defined in the literature and the definitions of hydrologic NRV are often based within the objectives of individual studies. Thus, for this study, the NRV of hydrologic variables was defined using a range of confidence intervals (80, 85, 90 and 95 percent). Confidence intervals are appropriate when addressing management questions as they provide both a measure of effect size (e.g. range of values) as well as including measures of uncertainty or risk (e.g. a 95% CI is equal to $\alpha = 0.05$) (Johnson, 1999). The range in confidence intervals was used to determine the bounds of 'acceptable' deviation (e.g. human influenced change) from the natural range of hydrologic variation and create a management framework based on quantifying the risks related to exceeding the hydrologic NRV within a region (Figure 4-2).

4.2.3 Application to forest management

The application of this chapter in a forest management context will help explore whether specific criteria and indicators for assessment of hydrologic impacts from forest harvesting should be applied on regional or provincial basis. Presently, a province wide threshold is used to assess impacts from proposed timber operations on water quality, quantity, and flow regime. The maximum allowable increase in projected mean annual water yield is a threshold of 15 percent (ASRD, 2006; Timber Harvesting and Operating Ground Rules Framework for Renewal, Watershed Protection; [6.0.2 – water yield]); any increase above this level will result in the re-evaluation of planned harvesting sequences within the forest management plan.

In this study ECA Alberta Version 1.0 (Silins, 2002) was used to quantify the effects of forest disturbance on regional mean annual water yields. ECA Alberta 1.0 (Silins, 2002) is a cumulative disturbance effects assessment tool used in integrated forest watershed planning and is based on the Equivalent Clearcut Area (ECA) concept. The ECA concept describes the temporal recovery of forest disturbances by quantifying the hydrologic footprint on an areal basis, which diminishes over time as evapotranspiration processes recover with the re-growth of the forest. For example, a 500 hectare disturbance that was created in 1980 and has regenerated over a time period of 20 years might be consuming 75 percent of the available water of which a mature stand of the same species would be utilizing. This would equate to an ECA of a 125 hectare disturbance (in terms of water use) if it was measured in 2010, approximately 20 years after disturbance.

The ECA Alberta integrated forest watershed planning and assessment model (Silins, 2002) is a strategic tool used in Alberta by forest companies and provincial governments for estimating increases to annual streamflows as a result of forest disturbance at a coarse (annual) scale. The ECA Alberta version is based on ECA concepts and incorporates components of the U.S. EPS WRENSS (Water Resources Evaluation of Non-Point Silvicultural Sources) model with revisions that simulate hydrologic recovery of landscapes to Alberta-specific forest growth and productivity. This revised model provides a relatively simple method to evaluate hydrologic effects of past, present and future disturbance on streamflow within a watershed; and additionally, predicts the hydrologic recovery of the system with time. The model simulates streamflow and hydrologic recovery at an annual time step (e.g. mm/yr or ECA ha or percent). The accuracy of the model is dependant on the information used to describe the hydrologic recovery of forest stands after disturbance (e.g. forest growth and yield tables) and the availability of regional streamflow and precipitation data. Model inputs are based on basic forest stand information (species, stand area, year of disturbance, and site quality). Inputs of watershed area and hydro-climatic setting (long term average precipitation and streamflow records) are also required. Model output is expressed as a change in ECA (hectares and percent) and annual water yield (area weighted [mm/year] and percent). To determine the hydrologic recovery of a forest stand this analysis is typically projected over time, usually the stand age to rotation (~ 100 years). To determine the maximum projected changes to the NRV for selected hydrologic variables, model outputs for the first year after disturbance (largest potential change) were used.

The case study presented in this chapter focuses on quantifying the risk (by using confidence intervals) of exceeding the hydrologic NRV that is associated with increasing levels of forest disturbance within a watershed. The hydrologic footprint of disturbance was measured using model outputs of ECA (percent harvested area) and the projected change to mean annual water yield (mm/year and percent). The proportional change for each hydrologic variable was determined by regression using ECA Alberta model outputs of the projected change in annual water yield and subsequent comparisons to the changes in the hydrologic NRV for selected hydrologic variables within each region (based on the derived relationships between hydrologic variables and mean annual regional streamflows) (Figure 4.2). This analysis allowed for exploration of potential thresholds for each hydrologic variable's NRV based on the projected changes to annual water yields.

4.2.4 Case study and scenario watershed description

To examine the regional changes in selected hydrologic characteristics with increasing levels of disturbance a fictitious study watershed was used. All model parameters were kept identical between six hydrologic regions with the exception of regionally specific variables related to mean annual precipitation and streamflow (Table 4-2). A watershed 1000 hectares (10 km^2) in size dominated by Pine, located on a good site index was used for each model scenario. Harvest levels were set at 100, 75, 50, 25 and 10 percent of total watershed area (1000, 750, 500, 250, and 100 hectares respectively) and were assessed separately by hydrologic region. Annual streamflows were calculated for each of the 211 study watersheds and then averaged to obtain mean annual regional streamflow values for each of the 6 hydrologic regions. Total annual precipitation was estimated for each study watershed using the ClimateAB Version 3.21 model (Wang *et al.*, 2006) with the geographic coordinates of hydrometric stations and the mean catchment elevation for input parameters. Mean precipitation was then calculated for each region. The ClimateAB 3.21 model allows for the projection and downscaling of long term normal climate data for Alberta to any resolution based on the PRISM (Parameter-elevation Regressions on Independent Slopes) data model, using spatial interpolation and elevation lapse rate adjustments (Hamann and Wang, 2005). Data derived using PRISM based models has been found superior to spatial interpolation using geographic information systems (GIS) with point based climate station data (Daily *et al.*, 1994).

In region 6, mean annual streamflow was greater than mean annual precipitation (Table 4-1), thus ECA Alberta model constraints (P must be greater than Q) did not allow for projection of changes to annual water yields. Given model constraints and the observation that region 6 catchments were located at high elevations and not within traditional forest management areas, their exclusion from analysis should not be detrimental to forest management implications. Region 4 was also excluded from the case study because of the few study watersheds within this region (n = 6), most of which were located outside of the forested landbase. ECA Alberta model outputs of percent ECA and projected increase in annual water yields were compared for each level of disturbance intensity across hydrologic regions. The projected increases in annual water yield were subsequently related to (1) current provincial thresholds and (2) the magnitude of change in additional hydrologic variables (using the relationships from regressions between mean annual regional streamflows and hydrologic variables calculated for each region).

4.3 Results

4.3.1 Relationships of regional hydrologic variables to mean annual regional streamflows

Streamflow variables related to magnitude (maximum daily Q and minimum seasonal Q) showed the most significant relationships and highest coefficients of determination (R^2) with mean annual regional streamflows across the six hydrologic regions. Maximum annual streamflows were positively correlated with mean annual regional streamflows for the four hydrologic regions. All comparisons were found to be significant ($P < 0.001$) with R^2 values ranging from 0.74 to 0.84 (Table 4-3, Figure 4-3). Minimum annual seasonal streamflows had positive relationships with mean annual regional streamflows with R^2 values ranging from 0.08 to 0.59. However, only regions 1 and 5 showed a significant trend with mean annual regional streamflow ($P < 0.001$, $R^2 = 0.58$ and 0.59 respectively) (Table 4-3, Figure 4-3). Contrasting streamflow magnitudes, variables related to the timing of streamflows were less significant with most regional relationships having R^2 values less then 0.31. Relationships between the day of maximum streamflow and mean annual regional streamflows were not significant for region 1 ($P = 0.438$, $R^2 =$

0.01); but were significant for region 5 ($P < 0.001$, $R^2 = 0.31$), region 7 ($P = 0.005$, $R^2 = 0.31$) and region 8 ($P = 0.002$, $R^2 = 0.23$) (Table 4-3, Figure 4-5). The day of half annual flow showed weak relationships with variation in mean annual regional streamflows with only Region 5 showing a significant trend ($P = 0.035$, $R^2 = 0.07$) (Table 4-3, Figure 4-6). Hydrologic variables selected to represent measures of streamflow frequency and duration also showed poor relationships to mean annual regional streamflows. Significant relationships for the annual number of discrete high flows were found in region 5 ($P < 0.001$, $R^2 = 0.41$) and region 1 ($P = 0.002$, $R^2 = 0.13$) (Table 4-3, Figure 4-7). Other variables in this category (number of discrete low flows, number of seasonal low flows and duration of seasonal low flows) showed weaker relationships with mean annual regional streamflows. The number of discrete low flows were only significant for regions 1 ($P = 0.034$, $R^2 = 0.06$) and 8 ($P = 0.049$, $R^2 = 0.10$) (Table 4-3, Figure 4-8). Regions found to have significant relationships with the number of seasonal low flows and the variation in mean annual regional streamflows were region 1 ($P = 0.041$, $R^2 = 0.06$) and region 8 ($P = 0.035$, $R^2 = 0.11$) (Table 4-3, Figure 4-9). The duration of seasonal low flows only showed a significant trend in region 8 ($P = 0.038$, $R^2 = 0.11$) (Table 4-3, Figure 4-10).

4.3.2 Hydrologic thresholds

Examination of relationships between mean annual regional streamflows and hydrologic variables showed no distinct changes in the relationships of any of the hydrologic variables with regional variation in annual regional streamflow. The lack of clear hydrologic thresholds suggested that using concepts of natural range of variation might serve as appropriate management thresholds. Descriptive statistics summarizing the NRV for each hydrologic variable were calculated across the six hydrologic regions using measures of central tendency and dispersion as well as the selected confidence intervals (Table 4-4). Mean annual streamflows showed large variation between hydrologic regions. The largest regional streamflows were observed in region 6 (935.8mm/year), followed by region 1, 5, 8, 4 and 7 with mean annual regional streamflows of 315.6, 124.7, 51.5, 39.6, and 24.7mm/year respectively. Patterns of variance followed a similar order, although region 4 showed more variability in annual streamflows then region 7 or 8. The NRV for maximum daily streamflows was largest and the most variable for regions located in the green zone (regions 6, 1 and 5) with the white zone regions (4, 7 and 8) having lower maximum streamflows that were less variable. Region 6 had the largest confidence interval ranges compared to other regions for all measure of streamflow magnitudes (average, maximum and minimum Q). Minimum seasonal streamflows followed similar regional patterns to maximum streamflows with regions 6, 1 and 5 ranging from 1.7 to 0.1 mm/day and regions 4, 7 and 8 ranging from 0.046 to 0.001 mm/day during the months of July to September. The timing of streamflows also followed a spatial gradient with later Julian dates of maximum streamflow and half annual flow dates occurring in regions 6, 1 and 5 with regions 4, 7 and 8 having earlier Julian dates. The NRV among the dates of maximum streamflow and half annual flows were considerably larger in the white zone regions (4, 7 and 8) then green zone regions (6, 1 and 5) causing confidence intervals to have larger ranges, especially in region 4. Contrasting the large differences observed in measures of streamflow magnitude and timing, regional differences in the frequency and duration of high and low streamflows were smaller and less variable. The annual number of high flows ranged from 5.9 (region 6) to 4.2 (region 7) and the annual number of low flows ranged from 2.1 (regions 6 and 1) to 1.3 (region 7). The variance in the number of high flows was largest for region 5 and lowest for region 4, whereas for the number of low flows the variance was largest for region 6 and lowest for region 7 (Table 4-4). The annual number and duration of seasonal low streamflow events did not differ considerably between regions, however white zone regions showed more frequent seasonal low flows, of longer duration than green zone regions 1 and 5. In region 6 there were no observed low flow events during months of July through September. Regions 4 and 8 showed the largest NRV for seasonal low flow frequency and duration followed by region 7; patterns of NRV did not differ substantially between region 1 and 5.

4.3.3 Forest management case study

ECA Alberta 1.0 outputs of projected increases to mean annual water yield for each harvest level differed considerably between the 4 hydrologic regions. These results demonstrate that a differential level of hydrologic sensitivity to forest harvesting exists across the province. Region 1 (Rockies) remained below the regulatory 15 percent threshold of a maximum increase in mean annual water yield until over 75 percent of the catchment had been harvested. Region 5 (Foothills/Boreal) exceeded the provincial regulatory threshold at harvest levels between 10 and 25 percent ECA. In regions 7 and 8 the regulatory threshold was exceeded at the lowest level of modeled disturbance (10 percent of the watershed area) (Table 4-5).

To examine the proportional change to hydrologic variables that were representative of streamflow magnitude, timing, frequency and duration the projected increases of annual water yield were added to regional average streamflows and substituted into regression relationships predicting changes to each hydrologic variable (Table 4-3). To determine if the NRV for each hydrologic variable was exceeded for the 5 harvesting scenarios the incremental change in hydrologic variable was compared to calculated confidence intervals. The results presented below are based on a threshold of the 95 percent confidence interval of hydrologic NRV. The 95 percent confidence interval represents the lowest-risk forest management case study scenario (e.g. the forest manager should be confident that hydrologic impacts for a given harvesting scenario are within the hydrologic NRV 95 percent of the time).

4.3.3.1 Magnitude of Streamflows

Hydrologic variables related to streamflow magnitudes (maximum daily streamflows [mm/day] and minimum daily seasonal streamflows [mm/day]) showed positive trends with increasing harvest levels (Table 4-6). Region 5 remained within the NRV of maximum daily streamflows for all harvesting scenarios. In region 1, the NRV of maximum daily streamflow was not exceeded until over 75 percent of the watershed was harvested (which was also the harvest scenario at which mean annual water yields exceed the 15 percent regulatory threshold) (Table 4-5). In regions 7 and 8 the NRV of maximum daily streamflows was exceeded at lower harvesting scenarios of 25 and 50 percent ECA respectively. Minimum seasonal streamflows showed a different response to harvesting scenarios. The NRV of minimum seasonal streamflow in region 1 remained within the bounds of the 95 percent confidence interval NRV for all harvesting scenarios. The minimum seasonal streamflows in region 5 showed the greatest sensitivity to harvesting, exceeding the NRV at the lowest ECA of 10 percent, whereas for regions 7 and 8 the NRV was not exceeded until harvesting scenarios reached 25 percent and 50 percent respectively.

4.3.3.2 Timing of Streamflows

The changes to the timing of streamflows as harvested area increased was a shift to later calendar dates of maximum and annual half flows (Table 4-7). This suggests that as forest disturbance increases, the temporal distribution of streamflow regimes are prolonged (drawn out later into the year). Relationships between the day of maximum streamflow and mean annual regional streamflows were not significant for region 1 but were significant in regions 5, 7, and 8. The timing of maximum daily streamflow in region 5 was the least sensitive to disturbance and remained within the 95 percent confidence interval NRV for all harvesting scenarios. Regions 7 and 8 where the most sensitive to disturbance, both of which exceeded the NRV for the timing of maximum daily streamflows at the lowest harvesting scenario (10 percent). The dates of half annual regional streamflows did not show strong relationships with regional mean streamflows. The only region showing a significant relationship was region 5 for which the NRV of half flow dates were exceeded at an ECA of 25 percent. All other regions (1, 7 and 8) did not show statistically significant relationships between dates of half annual regional streamflows and mean annual regional streamflows (Table 4-3).

4.3.3.3 Frequency and Duration of Streamflows

Hydrologic variables selected to represent measures of streamflow frequency and duration were the number of discrete high, low and seasonal low streamflows (July to September) as well as the duration of seasonal low streamflows. Although significant relationships were evident between the numbers of high flows and mean annual regional streamflows in regions 1 and 5, trends were opposite between regions (Table 4-8, Figure 4-7). In region 1, the number of high flows showed a decreasing trend with higher ECA scenarios, whereas the opposite was observed in region 5 with the frequency of high flow events becoming greater as harvest scenarios increased in ECA. Relationships between the number of low flow events and regional annual mean streamflows were only significant for regions 1 and 8 and although both were significant and positively related, the NRV was not exceeded for any harvesting scenario (Table 4-8). The number of seasonal low streamflows was significant for both region 1 and 8, both showing a decrease in the frequency of seasonal low flows as the percent ECA was increased (Table 4-9). The NRV in seasonal low flows was not exceeded in region 1 for any harvesting scenario, whereas the NRV in region 8 was exceeded at the lowest level of ECA. Regions 5 and 7 did not have a significant relationship with regional climatic gradients; however, both showed increasing trends in the frequency of seasonal low streamflows with increasing ECA levels. In region 8, the NRV of the duration of seasonal low streamflows showed a decreasing trend with increasing harvest levels but remained within the 95 percent confidence limits of NRV for all scenarios (Table 4-9).

4.4 Discussion

4.4.1 Regional differences in hydrologic thresholds

The results of this study highlighted large differences in the natural range of hydrologic variation between regions across the forested landbase of Alberta. Within each hydrologic region, different levels of hydrologic sensitivity were observed using the ECA Alberta model 1.0 (Silins, 2002) to predict changes in mean annual regional streamflows for five different forest management scenarios (Table 4-5). The predicted changes to mean annual regional streamflows were then related to relationships between hydrologic variables observed to co-vary with the variation in mean annual regional streamflows (e.g. dry to wet years). Regions located in the higher elevation Rocky Mountains (e.g. region 1) showed the lowest level of hydrologic sensitivity to forest disturbances. In this region the current regulatory threshold was not exceeded until over 75 percent of the watershed had been harvested. Region 5, spanning the lower foothills and Boreal forest regions of Alberta, showed greater hydrologic sensitivity to forest harvesting scenarios. The regulatory threshold in region 5 was exceeded between an ECA of 10 and 25 percent. These 2 regions (1 and 5) cover most of the publicly owned forest land in Alberta (the green zone) where the majority of industrial forestry operations occur. The remaining two regions (7 and 8) were located in lands zoned as agricultural (white zone). Although these regions are not actively managed for forestry use, they do have moderate amounts of forest cover ranging from 25 to 35 percent. Regions 7 and 8 showed the greatest hydrologic sensitivity to forest harvesting scenarios. In both regions the predicted changes in annual water yield exceeded the regulatory threshold of 15 percent for the lowest harvesting scenario which was set at 10 percent ECA.

The differential levels of sensitivity observed between hydrologic regions can be attributed to the proportion of regional precipitation inputs to regional streamflow outputs (Table 4-2). Watersheds located in the western parts of the province (region 1) receive large amounts of precipitation, most of which is generated into streamflow (high runoff ratios). The north-east of the province (regions 5, 7 and 8) has less precipitation and significantly less streamflow (lower runoff ratios). Differences in runoff ratios between regions are a combined result of climatic and physiographic controls and their interaction amongst each other. Regional physiographic differences, examined in chapter 3, are known to influence the hydrologic response of watersheds. Steeper slopes and greater topographic variation (e.g. relief) are found in the west, whereas basins in the north-eastern part of the province have lower topographic variation and significantly lower slopes. Differences in storage capacity and evaporative demand are also present between regions. Watersheds in the west are dominated by bedrock and colluvium materials overlain by shallow soils, whereas deeper glacial tills and fluvial deposits overlain by more developed soils are characteristic of eastern Boreal landscapes (Downing and Pettapiece, 2006). These physical characteristics create stronger hydrologic gradients for streamflow generation and reduced potential for soil storage opportunities in the western parts when compared to the north eastern parts of the province. Evaporative demand is considerably greater at lower elevations due to precipitation inputs, mostly resulting from summer rain events coinciding with peak water demand by vegetation and resulting in little available water to generate runoff, particularly after soil recharge occurs. In the western parts of the province, most precipitation is in the form of snow, the majority of which is observed during the spring freshet. These higher elevation watersheds have cooler temperatures, a shorter growing season and lower ET demands. The differences in physiographic and climatic controls exemplify why hydrologic behaviour differs across the province and provides insights into the observed differences in hydrologic response and sensitivity to forest disturbance across regions.

4.4.2 Hydrologic response to harvest scenarios

By developing regional relationships between mean annual regional streamflows and regional hydrologic characteristics, a coarse scale evaluation of the effects of forest disturbance on hydrology could be explored through the use of commonly applied forest management hydrologic models. This analysis was completed under 3 assumptions (1) the temporal variation in annual regional mean streamflows is representative of the annual temporal variation of regional climates (e.g. years having higher annual streamflows are representative of years with higher annual precipitation) (2) forest disturbance (e.g. harvesting) generally increases the amount of water available for generation of runoff, and (3) within a region, low annual streamflows were representative of dryer conditions (e.g. unharvested watersheds) and higher streamflows were representative of wetter conditions (e.g. harvested watersheds). These assumptions are considered realistic as analyses were completed by hydrologic region characterized by having homogeneous hydrologic characteristics.

By using the ECA Alberta model 1.0 (Silins, 2002) to explore five scenarios, each with increasing levels of forest disturbance analysis, it was demonstrated that hydrologic variables related to measures of magnitude (maximum daily streamflows and minimum seasonal streamflows) were the most sensitive and significant to regional changes in mean annual regional streamflows. Minimum seasonal streamflows were the most sensitive in region 5 and the least sensitive in region 1. These analyses suggest differential levels of sensitivity exist across regions and furthermore that sensitivity is specific to the hydrologic variable being examined. The timing of maximum streamflow was not as sensitive to forest disturbance as streamflow magnitudes, particularly in forested regions 1 and 5. Reasons for this might be due to the day of maximum streamflow corresponding to the peak of the snowmelt freshet, and therefore, not being a representative indicator of hydrologic change. The timing of half annual streamflow dates showed similar patterns with later dates of occurrence being observed at greater levels of forest disturbance. The sensitivity in the frequency and duration of streamflows (high, low and seasonal low streamflows) was most evident for region 5 in which the 95 percent NRV threshold was exceeded at an ECA of only 10% for both high, low and seasonal low streamflows. Conversely, region 1 was the least sensitive to high, low and seasonal low streamflows and remained within the 95 percent NRV for all harvest scenarios.

Relationships between hydrologic variables and mean annual regional streamflow were not always consistent between hydrologic regions. In region 1 (Rockies), the number of high streamflow decreased with increasing mean annual regional streamflows, but in region 5 (foothills/Boreal) high flows increased with wetter conditions. This divergent trend between the two regions questions the method by which the frequency of high streamflows was calculated. High flows were defined as events which were less then or equal to the 10^{th} percentile of the flow duration curve. A discrete high flow event can be a result of two distinctly unique hydrological processes (1) snowmelt events and (2) precipitation events. In region 1, high flows are primarily driven by snowmelt and reflected in the single peaked nature of hydrographs. In region 5, high flows are also a result of snowmelt, but convective atmospheric conditions generate summer thunderstorms and create additional precipitation peaks in the annual hydrograph. As climatic conditions in region 1 become increasingly wetter, the 10^{th} percentile of the annual FDC may be unduly influenced by large snowmelt freshets, causing any high flow events from subsequent precipitation events to be under the 10^{th} percentile exceedance probability threshold. In region 5, a year with larger streamflows may be more reflective of more precipitation events during the summer as opposed to a heavy winter snowpack; this would result in the number of high flows to increase as climatic conditions become wetter. These observations confound the analysis of high flow events and made interpretation of forest disturbance scenarios for high flows difficult to evaluate. However, this highlights the difficulty in accurately selecting (and calculating) hydrologic variables for scientifically defensible criteria and indicators for providing a framework to evaluate the risks of impacting water resources as a result of proposed forest management plans.

4.4.3 Application to a risk management framework

The work presented here has attempted to create a management framework that will enable forest managers to more accurately quantify and understand the risks that proposed forest management plans (FMP's) may have on regional hydrologic behaviour at a coarse spatial and temporal scale. By using confidence intervals to define the hydrologic NRV, the degree of departure from hydrologic NRV can be evaluated both in terms of the risk (e.g. the probability of it occurring) and the consequence (e.g. the size of the effect). What needs to be emphasized is that a different level of risk may be present depending on the location of planned forest management activities and the related goals and objectives of the forest management plan. For example, the risk of exceeding the NRV for maximum streamflows may be quite low in a given watershed, but the consequences of exceeding the NRV of maximum streamflows may cause significant social or ecological damage downstream in the form of a large flood. With this in mind managers may choose a lower level of flood risk by comparing analysis results of a 95 percent NRV confidence interval to that of an 80 percent NRV confidence interval. This will allow forest managers to quantitatively manage the risk of negative hydrologic impacts and evaluate potential social and ecological tradeoffs of management decisions for achieving the goals and objectives of the FMP.

Another important observation made during this study was that the choice of hydrologic variables to consider cannot be standardized. Depending on management goals and objectives, certain hydrologic variables will have greater emphasis on FMP planning decisions. For example, water resources managers may be concerned with changes to the timing and delivery of water to reservoirs for ensuring adequate water supply to downstream users; or the sensitivity of aquatic ecosystems in a region may be adversely impacted by changes to the frequency and duration of streamflows for habitat requirements. In areas with stressed water supplies projected increases in annual water yields might be a beneficial by-product of forest management activities, but additional hydrologic changes accompanying larger water yields must be considered carefully and evaluated for impacts to other values (Figure 4-2). These situations are examples of how different management goals will direct the choice of hydrologic variables to be evaluated. Over 200 hydrologic variables have been used in water resources sciences, all of which are considered important from a management, societal or ecological perspective (Olden and Poff, 2003); however, the choice of which hydrologic variable is the most relevant will depend on the specific research questions, management goals and objectives, and regional issues of concern and relationships to forest management planning tool outputs.

4.5 Conclusion

This study explored the projected impacts of forest disturbance on regional streamflow regimes across Alberta's forested landbase to support the development and evaluation of forest management plans (FMP) in the context of sustainable forest management for water resources. Integrated watershed planning is a mandatory component of forest management in Alberta, but no framework or tool currently exists that uses scientifically defensible criteria and indicators for evaluating the projected changes to hydrology or to hydrologic indicators of social, ecological or management interest that forest harvesting may cause. This study has explored the potential for linking current management planning tools to quantifiable relationships describing regional hydrologic response based on a risk assessment framework. Although specific management based targets were not identified, information was presented that will provide guidance for the evaluation of the risks of exceeding the NRV for most aspects of the streamflow regime. With this framework, scientifically defensible criteria and indicators describing the hydrologic NRV were developed, helping to provide additional information for land managers to identify and evaluate the tradeoffs of impacting water resources as a result of proposed forest management plans.

Table 4-1 Sub-set of non-redundant hydrologic variables associated with gradients in mean annual streamflow (also shown) that are broadly representative of the streamflow regime. Units of measurement are denoted in brackets.

Flow Category	Hydrologic Variable	Description
Streamflow Magnitude		
	Mean Annual Streamflow (mm/year)	Cumulative streamflow for each year of record
	Maximum Daily Streamflow (mm/day)	Maximum daily streamflow for each year of record
	Minimum Seasonal Streamflow (mm/day)	Minimum streamflow occurring during the months of July to September for each year of record
Streamflow Timing		
	Day of Maximum Streamflow (DOY)	Julian day of maximum daily streamflow occurring for each year of record
	Day of Half Annual Streamflow (DOY)	Julian day at which 50% of the annual streamflow has occurred for each year of record
Streamflow Frequency		
	Annual Number of High Flows	Number of discrete high flow events > or = to the 10th percentile of the annual FDC value for each of record
	Annual Number of Low Flows	Number of discrete low flow events < or = to the 90th percentile of the annual FDC value for each of record
	Annual Number of Seasonal Low Flows	Number of discrete low flow events < or = to the 90th percentile of the annual FDC value during July to September for each of record
Streamflow Duration		
	Annual Duration of Seasonal Low Flows	Duration of discrete low flow events < or = to the 90th percentile of the annual FDC value during July to September for each of record

Table 4-2 Estimated mean annual precipitation (mm/year), mean annual streamflow (mm/year) and calculated runoff ratios in descending order for each of the six hydrologic regions.

Hydrologic Region	Precipitaion based on 1961-2000 long term climate normals (mm/year)	Mean Streamflow (mm/year)	Runnoff Ratio (mm/year)
6	666	936	1.41
1	496	312	0.63
5	507	127	0.25
8	486	52	0.11
4	431	39	0.09
7	450	25	0.05

Table 4-3 Relationships between selected hydrologic variables and mean annual regional streamflow by hydrologic region. Bolded P values indicate a statistically significant relationship (α = 0.05). Regression equations shown were used for calculating the expected change in hydrologic variables with the projected change in annual water yield as a result of forest disturbance.

Variable	Region	d f	R-Square	F-stat	p value	Equation
Maximum Daily Streamflow (mm/day)	1	70	0.74	200.3	**< 0 .001**	y = 0.0196x + 2.4804
	5	60	0.75	177.7	**< 0 .001**	y = 0.056x - 1.4782
	7	22	0.76	67.4	**< 0 .001**	y = 0.1361x - 0.466
	8	38	0.84	197.7	**< 0 .001**	y = 0.0846x - 0.7304
Minimum Seasonal Streamflow (mm/day)	1	70	0.58	95.0	**< 0 .001**	y = 0.0012x + 0.0465
	5	60	0.59	84.4	**< 0 .001**	y = 0.001x + 0.0151
	7	22	0.36	11.6	**0.003**	y = 0.000061x - 0.0001
	8	38	0.08	3.3	0.076	y = 0.0001x + 0.0049
Day of Maximum Annual Streamflow	1	70	0.01	0.6	0.438	y = 0.0066x + 162.2
	5	60	0.31	26.5	**< 0 .001**	y = 0.0938x + 155.56
	7	22	0.31	9.6	**0.005**	y = 0.428x + 105.82
	8	38	0.23	10.8	**0.002**	y =0.2495x + 123.24
Day of Half Annual Streamflow (DOY)	1	70	0.02	1.1	0.289	y = 0.0087x + 172.38
	5	60	0.07	4.7	**0.035**	y = 0.0402x + 165.67
	7	22	0.00	0.0	0.931	y = -0.015x + 120.21
	8	38	0.01	0.4	0.519	y =0.0413x + 140.89
Annual Number of High Flows	1	70	0.13	10.4	**0.002**	y = -0.0023x + 5.0288
	5	60	0.41	41.3	**< 0 .001**	y =0.0137x + 2.972
	7	22	0.05	1.1	0.310	y = -0.0183x + 4.631
	8	38	0.00	0.1	0.757	y =0.0021x + 4.3503
Annual Number of Low Flows	1	70	0.06	4.7	**0.034**	y = 0.002x + 1.4647
	5	60	0.00	0.1	0.077	y = 0.0006x + 1.7728
	7	22	0.07	1.5	0.235	y = -0.0075x + 1.4782
	8	38	0.10	4.1	**0.049**	y = 0.0143x + 1.1875
Annual Number of Seasonal Low Flows	1	70	0.06	4.3	**0.041**	y = -0.0003x + 0.1888
	5	60	0.05	3.2	0.078	y =-0.0007x + 0.2233
	7	22	0.08	1.7	0.204	y = -0.0057x + 0.2441
	8	38	0.11	4.8	**0.035**	y = 0.0078x + 0.0073
Annual Duration of Seasonal Low Flows	1	70	0.05	3.3	0.073	y = -0.0011x + 0.7021
	5	60	0.06	3.6	0.064	y = -0.0045x + 1.2381
	7	22	0.01	0.3	0.586	y = -0.0164x + 1.0116
	8	38	0.11	4.6	**0.038**	y = 0.0363x - 0.1109

Table 4-4 Descriptive statistics (shown by hydrologic region) of the selected hydrologic variables and their natural range of variation (NRV) denoted by a range of confidence intervals (+/- value).

Mean Annual Streamflow (mm/year)

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	935.8	814.0	417.7	174501.0	498.0	1862.4	272.9	229.0	200.4	178.4
1	315.6	279.0	179.3	32149.8	28.7	936.2	41.7	35.0	30.6	27.3
5	124.7	118.8	64.0	4101.3	19.1	318.1	16.1	13.5	11.8	10.5
8	51.5	47.1	27.7	766.9	2.2	125.2	8.7	7.3	6.4	5.7
4	39.6	32.4	36.0	1296.6	4.1	108.0	28.8	24.2	21.2	18.8
7	24.7	22.3	12.4	152.8	3.9	47.3	5.1	4.2	3.7	3.3

Maximum Daily Streamflow (mm/day)

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	15.3	11.7	10.7	114.5	5.2	39.5	7.0	5.9	5.1	4.6
1	8.7	8.2	4.1	16.6	1.4	19.6	0.9	0.8	0.7	0.6
5	5.5	4.4	4.1	17.1	0.4	16.5	1.0	0.9	0.8	0.7
8	3.6	2.8	2.6	6.5	0.1	9.0	0.8	0.7	0.6	0.5
4	1.5	1.7	0.7	0.5	0.4	2.3	0.6	0.5	0.4	0.4
7	2.9	2.7	1.9	3.7	0.3	6.7	0.8	0.7	0.6	0.5

Minimum Seasonal Streamflow (mm/day)

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	1.702	1.574	0.614	0.377	1.078	3.240	0.401	0.337	0.295	0.262
1	0.434	0.393	0.289	0.084	0.020	1.181	0.067	0.056	0.049	0.044
5	0.108	0.078	0.082	0.007	0.007	0.378	0.021	0.017	0.015	0.013
8	0.011	0.010	0.011	0.000	0.001	0.058	0.004	0.003	0.003	0.002
4	0.046	0.019	0.074	0.006	0.002	0.195	0.059	0.050	0.044	0.039
7	0.001	0.001	0.001	0.000	0.000	0.005	0.001	0.000	0.000	0.000

Day of Maximum Annual Streamflow (DOY)

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	190	190	14	196	171	211	9	8	7	6
1	164	164	13	159	123	201	3	2	2	2
5	167	169	11	116	130	185	3	2	2	2
8	136	139	15	212	99	159	5	4	3	3
4	126	117	17	285	112	148	14	11	10	9
7	116	116	9	89	102	132	4	3	3	3

Day of Half Annual Streamflow (DOY)

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	202	202	6	40	195	214	4	3	3	3
1	175	178	12	150	141	199	3	2	2	2
5	171	172	9	90	144	187	2	2	2	2
8	143	144	11	115	105	161	3	3	2	2
4	147	148	17	278	124	169	13	11	10	9
7	120	120	10	94	104	141	4	3	3	3

Table 4-4 (continued) Descriptive statistics (shown by hydrologic region) of the selected hydrologic variables and their natural range of variation (NRV) denoted by a range of confidence intervals (+/- value). Note: The number and duration of seasonal low streamflows for region 6 were absent; therefore region 6 is not shown for the number and duration of seasonal low streamflows

Annual Number of High Flows

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	5.9	6.0	1.1	1.1	3.5	7.1	0.7	0.6	0.5	0.5
1	4.3	4.3	1.1	1.3	2.0	6.6	0.3	0.2	0.2	0.2
5	4.7	4.6	1.4	1.9	1.8	7.5	0.3	0.3	0.3	0.2
8	4.5	4.3	1.1	1.3	2.3	7.2	0.4	0.3	0.3	0.2
4	5.4	5.4	0.7	0.5	4.2	6.2	0.6	0.5	0.4	0.4
7	4.2	3.8	1.0	1.0	2.9	7.4	0.4	0.4	0.3	0.3

Annual Number of Low Flows

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
6	2.1	1.2	1.4	2.1	1.0	4.7	0.9	0.8	0.7	0.6
1	2.1	1.5	1.4	2.0	1.0	5.8	0.3	0.3	0.2	0.2
5	1.8	1.5	0.9	0.9	1.0	5.1	0.2	0.2	0.2	0.2
8	1.9	1.3	1.2	1.6	1.0	5.6	0.4	0.3	0.3	0.3
4	2.0	1.6	1.2	1.5	0.9	4.4	1.0	0.8	0.7	0.7
7	1.3	1.1	0.4	0.1	1.0	2.2	0.1	0.1	0.1	0.1

Annual Number of Seasonal Low Flows

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
1	0.1	0.0	0.2	0.1	0.0	1.3	0.1	0.0	0.0	0.0
5	0.1	0.0	0.2	0.0	0.0	0.8	0.1	0.0	0.0	0.0
8	0.4	0.0	0.6	0.4	0.0	2.4	0.2	0.2	0.1	0.1
4	0.3	0.3	0.2	0.1	0.0	0.6	0.2	0.2	0.1	0.1
7	0.1	0.0	0.3	0.1	0.0	0.9	0.1	0.1	0.1	0.1

Annual Duration of Seasonal Low Flows

Region	Mean	Median	Std Dev	Variance	Minimum	Maximum	CI 95 (+/-)	CI 90 (+/-)	CI 85 (+/-)	CI 80 (+/-)
1	0.3	0.0	0.9	0.9	0.0	5.0	0.2	0.2	0.2	0.1
5	0.7	0.1	1.2	1.5	0.0	5.8	0.3	0.3	0.2	0.2
8	1.8	0.0	3.0	9.1	0.0	10.9	1.0	0.8	0.7	0.6
4	0.7	0.2	1.2	1.4	0.0	3.1	1.0	0.9	0.8	0.7
7	0.6	0.0	1.7	2.9	0.0	7.5	0.7	0.6	0.5	0.5

Table 4-5 ECA Alberta model (Silins, 2002) outputs for each harvesting scenario showing the predicted change for annual water yield in percent (%) and (mm/year) for the remaining four hydrologic regions. Shaded cells represent yields that are predicted to be above the regulatory threshold of a maximum increase in annual water yield of 15 percent.

Harvest Level (%)	**Predicted change in annual water yield (%)**			
	Region 1	Region 5	Region 8	Region 7
10	1.8	9.1	25.3	53.9
25	4.5	22.7	63.3	134.7
50	9.0	45.4	126.6	269.3
75	13.4	68.1	189.9	403.9
100	17.9	90.8	253.3	538.6

Harvest Level (%)	**Predicted change in annual water yield (mm/yr)**			
	Region 1	Region 5	Region 8	Region 7
10	5.6	11.5	13.2	12.9
25	14.0	28.8	32.9	32.3
50	27.9	57.7	65.8	64.6
75	41.9	86.5	98.8	96.6
100	55.8	115.3	131.7	129.3

Table 4-6 Regression results showing the predicted change to hydrologic variables describing streamflow magnitudes using relationships derived from model outputs of the predicted change in annual water yield (mm/yr) and hydrologic variables of maximum annual daily streamflow (mm/day) and the minimum annual seasonal streamflow (mm/day). Regions denoted with an asterisk (*) were statistically significant ($\alpha = 0.05$) and shaded values denote harvest scenarios within regions that exceed the 95 percent NRV confidence interval.

Predicted Change in Maximum Daily Streamflow (mm/day)

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1*	8.78	8.94	9.21	9.49	9.76
Region 5*	3.05	3.33	3.80	4.26	4.72
Region 8*	2.15	3.25	5.09	6.94	8.78
Region 7*	2.45	4.09	6.82	9.53	12.29

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	9.60	9.45	9.35	9.28
Region 5	6.54	6.38	6.27	6.18
Region 8	4.43	4.30	4.22	4.15
Region 7	3.68	3.55	3.47	3.41

Predicted Change in Minimum Seasonal Low Streamflow (mm/day)

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1*	0.4320	0.4421	0.4588	0.4756	0.4922
Region 5*	0.2396	0.2742	0.3320	0.3896	0.4472
Region 8	0.0798	0.0995	0.1324	0.1654	0.1983
Region 7*	0.0090	0.0112	0.0147	0.0182	0.0218

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	0.5013	0.4905	0.4834	0.4780
Region 5	0.1282	0.1249	0.1227	0.1211
Region 8	0.0145	0.0139	0.0135	0.0132
Region 7	0.0019	0.0018	0.0018	0.0017

Table 4-7 Regression results showing the predicted change to hydrologic variables describing streamflow timing using relationships derived from model outputs of predicted change in annual water yield (mm/yr) and hydrologic variables of day of maximum daily streamflow (DOY) and the day of half annual streamflow (DOY). Regions denoted with an asterisk (*) were statistically significant ($\alpha = 0.05$) and shaded values denote harvest scenarios within regions that exceed the 95 percent NRV confidence interval.

Predicted Change in Day of Maximum Daily Streamflow (DOY)

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1	164	164	164	165	165
Region 5*	141	143	148	152	156
Region 8*	162	163	167	170	173
Region 7*	133	137	146	153	162

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	167	167	166	166
Region 5	170	170	169	169
Region 8	141	140	139	139
Region 7	120	120	119	119

Predicted Change in Day of Half Annual Streamflow (DOY)

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1	175	175	175	175	176
Region 5*	172	177	185	192	200
Region 8	168	169	170	172	173
Region 7	142	143	145	146	147

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	178	178	177	177
Region 5	173	173	172	172
Region 8	146	146	145	145
Region 7	124	123	123	122

Table 4-8 Regression results showing the predicted change to hydrologic variables describing streamflow frequency using relationships derived from model outputs of predicted change in annual water yield (mm/yr) and hydrologic variables of the discrete number of high, low and seasonal low streamflow and the duration of seasonal low streamflows. Regions denoted with an asterisk (*) were statistically significant ($\alpha = 0.05$) and shaded values denote harvest scenarios within regions that exceed the 95 percent NRV confidence interval.

Predicted Change in Number of High Flows

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1*	4.3	4.3	4.2	4.2	4.2
Region 5*	6.2	6.3	6.6	6.8	7.0
Region 8	3.9	4.1	4.6	5.0	5.5
Region 7	4.4	4.5	4.5	4.6	4.7

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	4.6	4.5	4.5	4.5
Region 5	5.0	5.0	4.9	4.9
Region 8	4.8	4.8	4.7	4.7
Region 7	4.6	4.5	4.5	4.5

Predicted Change in Number of Low Flows

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1*	2.1	2.1	2.2	2.2	2.2
Region 5	5.2	5.8	6.8	7.7	8.7
Region 8*	1.8	1.8	1.8	1.9	1.9
Region 7	1.7	2.0	2.5	2.9	3.4

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	2.4	2.4	2.3	2.3
Region 5	2.1	2.0	2.0	2.0
Region 8	2.3	2.3	2.2	2.2
Region 7	1.4	1.4	1.4	1.4

Table 4-9 Regression results showing the predicted change to hydrologic variables describing seasonal streamflow frequency and duration using relationships derived from model outputs of predicted change in annual water yield (mm/yr) and hydrologic variables of the discrete number seasonal low streamflow and the duration of seasonal low streamflows. Regions denoted with an asterisk (*) were statistically significant ($\alpha = 0.05$) and shaded values denote harvest scenarios within regions that exceed the 95 percent NRV confidence interval.

Predicted Change in Number of Seasonal Low Flows

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1*	0.09	0.09	0.09	0.08	0.08
Region 5	0.33	0.35	0.37	0.39	0.42
Region 8*	0.18	0.16	0.14	0.12	0.10
Region 7	0.30	0.45	0.70	0.95	1.21

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	0.14	0.13	0.13	0.12
Region 5	0.18	0.18	0.17	0.17
Region 8	0.61	0.58	0.55	0.54
Region 7	0.21	0.19	0.18	0.17

Predicted Change in Duration of Seasonal Low Flows

	10% ECA	25% ECA	50% ECA	75% ECA	100% ECA
Region 1	0.35	0.34	0.32	0.31	0.29
Region 5	0.76	0.77	0.78	0.79	0.80
Region 8*	0.95	0.86	0.71	0.56	0.41
Region 7	1.25	1.96	3.13	4.29	5.48

Maximum allowable change (+/- the mean) for selected confidence interval

	CI 95	CI 90	CI 85	CI 80
Region 1	0.57	0.53	0.51	0.49
Region 5	0.98	0.93	0.90	0.87
Region 8	2.70	2.55	2.45	2.37
Region 7	1.30	1.19	1.12	1.06

Figure 4-1 Map of Alberta showing six hydrologic regions obtained from hierarchical cluster analysis of hydrograph shape variables. The light grey area shows the boundary between green zone and national parks (forested) and the white zone (mostly agricultural).

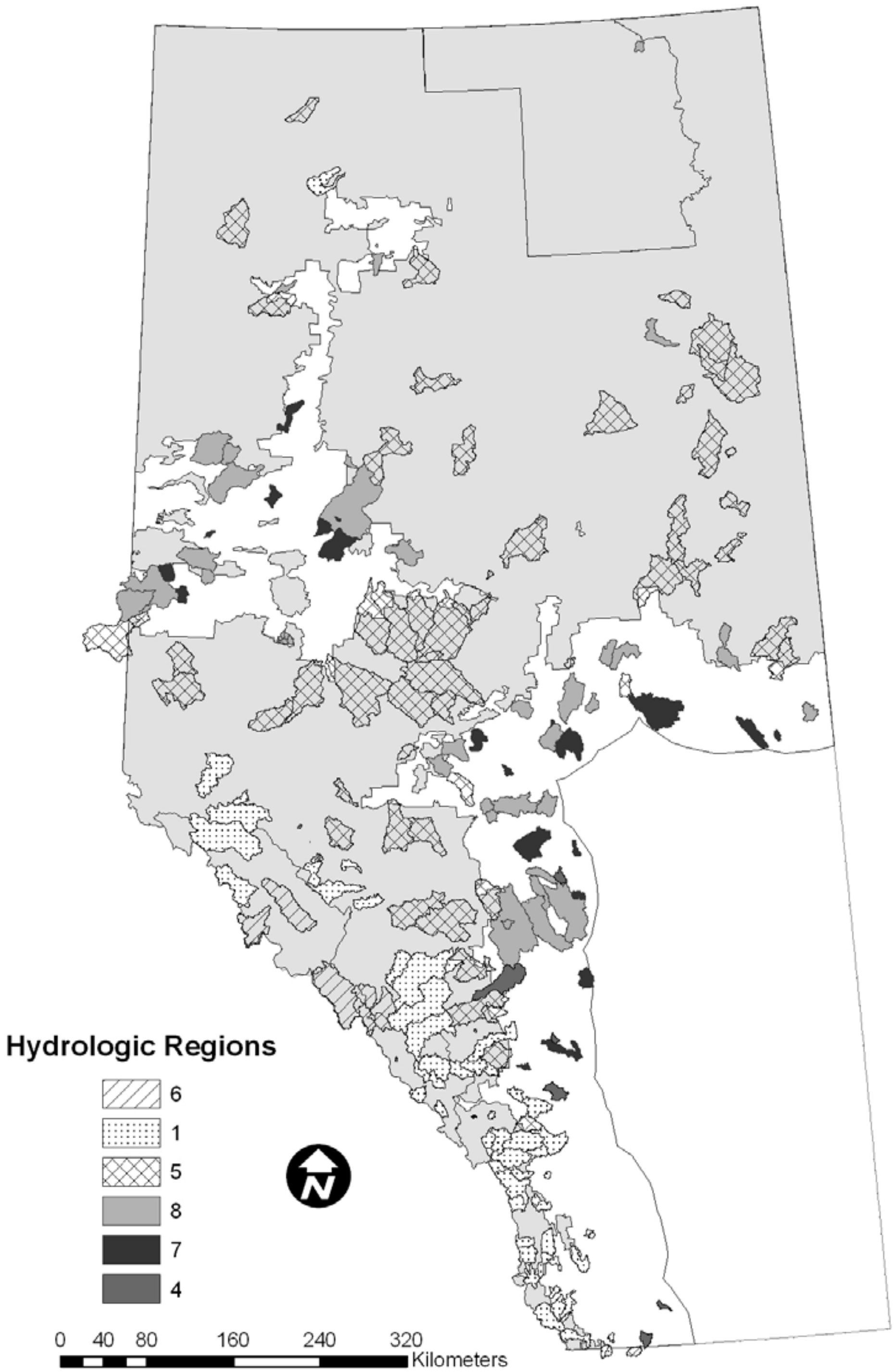


Figure 4-2 Example schematic of how confidence intervals can be used to evaluate if projected changes to annual water yield will cause the NRV of a related hydrologic variables to be exceeded. The inner dashed lines are the 80% confidence interval limits and the outer dashed lines denoting limits of the 95% confidence interval. In Scenario 1, a change in mean annual water yield of approximately 20mm/year (Δ in Qa to Qb) results in the NRV of hydrologic variable Y to be exceeded (outside of 80 and 95% NRV range). Scenario 2 shows a change in annual water yield of approximately 10mm/year (Δ in Qa to Qb) resulting in the NRV of hydrologic variable Y to remain inside the 95% NRV confidence interval, but outside the 80% range.

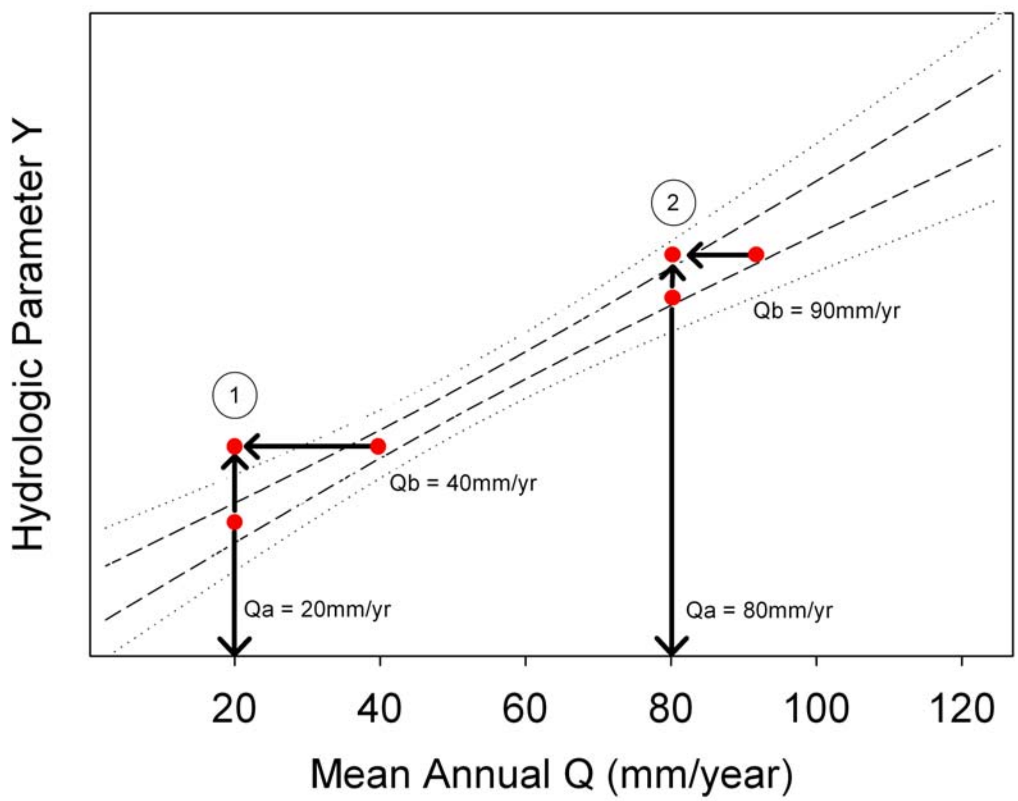


Figure 4-3 Relationship between maximum 1 day annual streamflow (mm/day) and the change in mean annual regional streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression ($\alpha = 0.05$). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

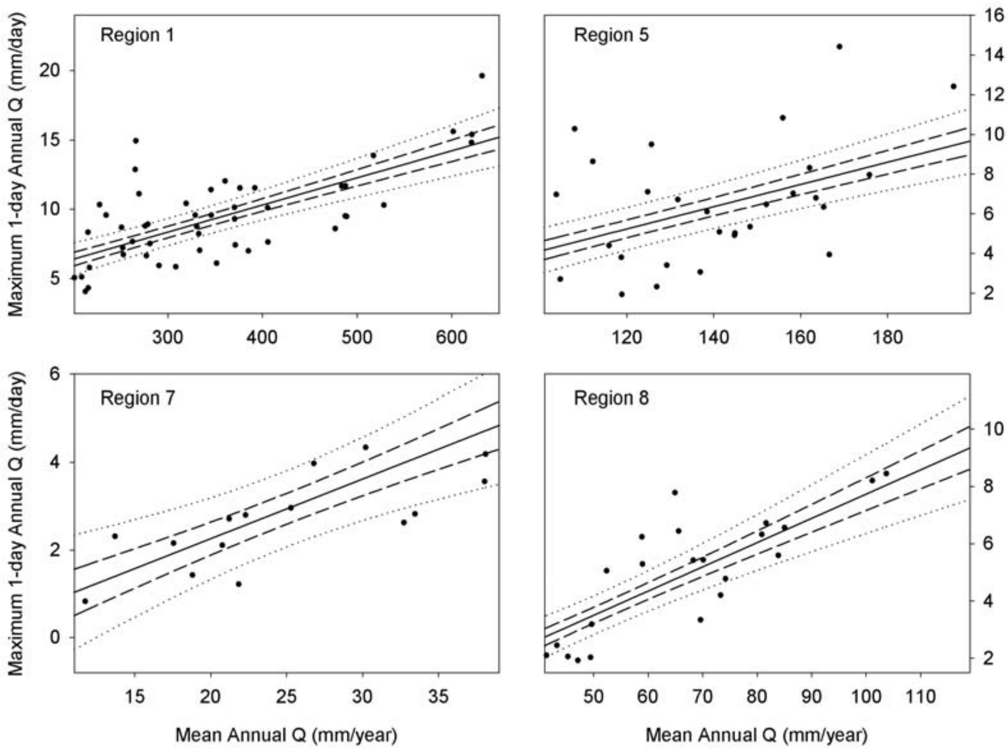


Figure 4-4 Relationship between minimum seasonal streamflow (mm/day) and the change in mean annual regional streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression (α = 0.05). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

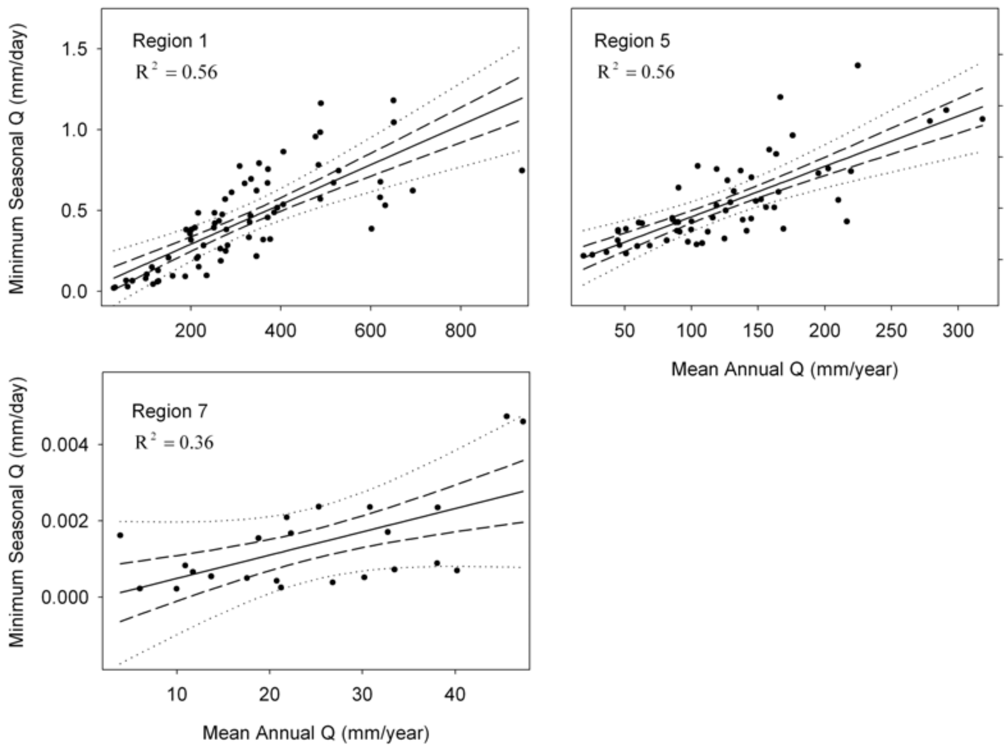


Figure 4-5 Relationship between the day of maximum annual streamflow (mm/day) and the change in mean annual regional streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression ($\alpha = 0.05$). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

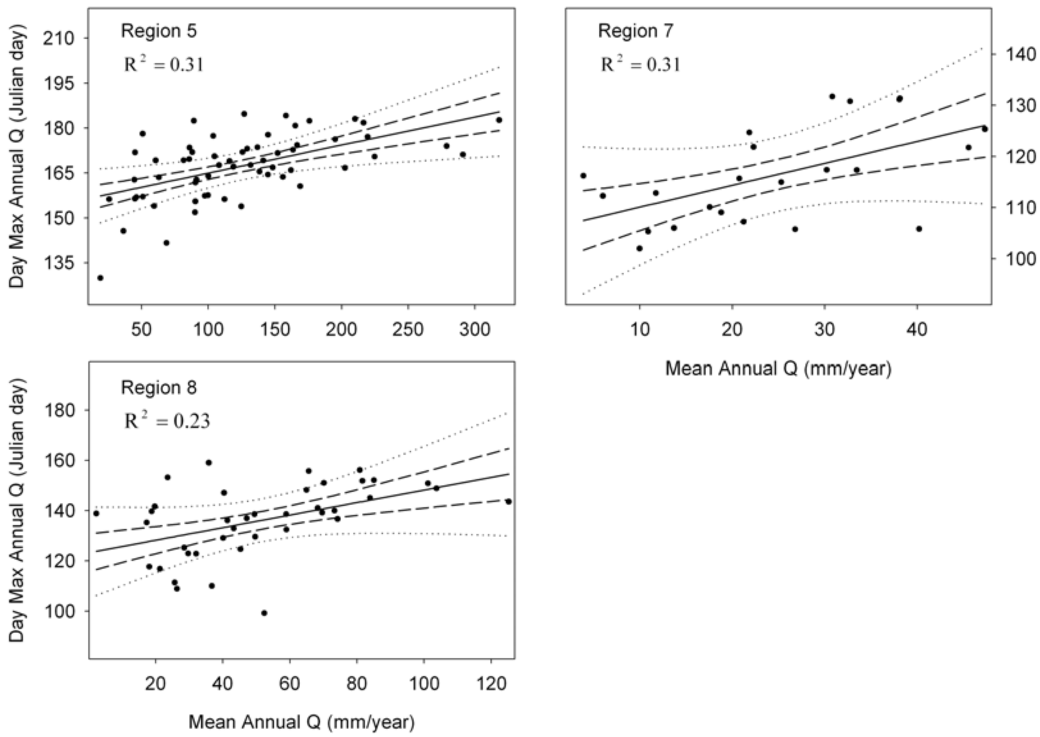


Figure 4-6 Relationship between the day of half annual streamflow (Julian day) and the change in mean annual regional streamflow (mm/year) for region 5. Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

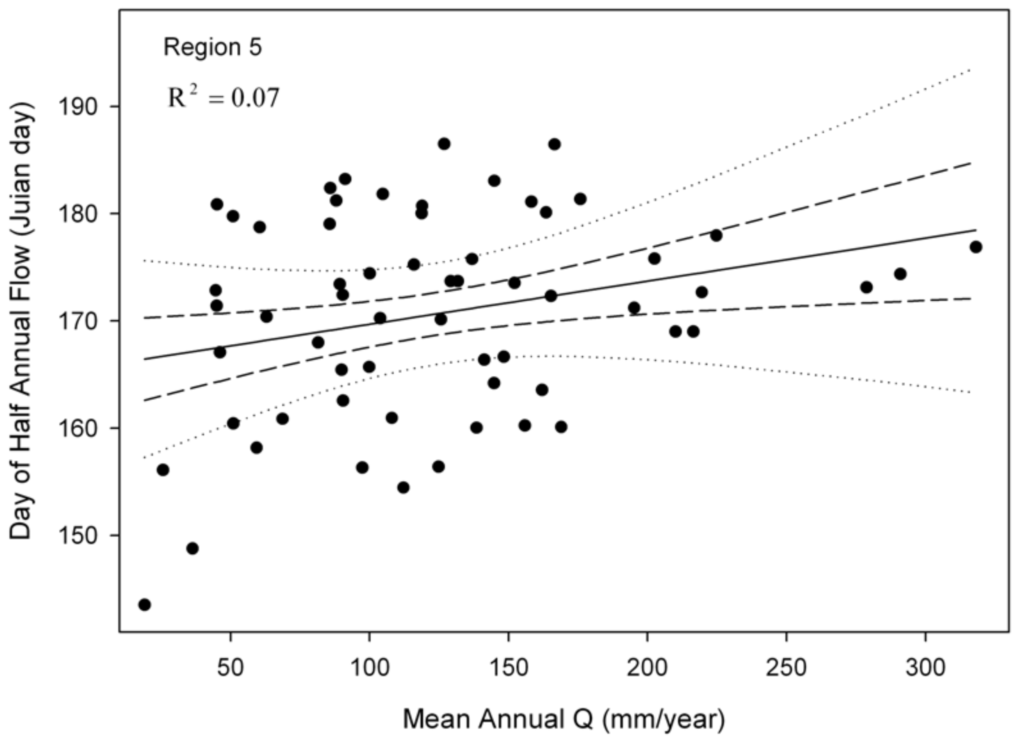


Figure 4-7 Relationship between the number of discrete high flows and the change in mean annual regional streamflow for hydrologic regions that were found to be significant by linear regression ($\alpha = 0.05$). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

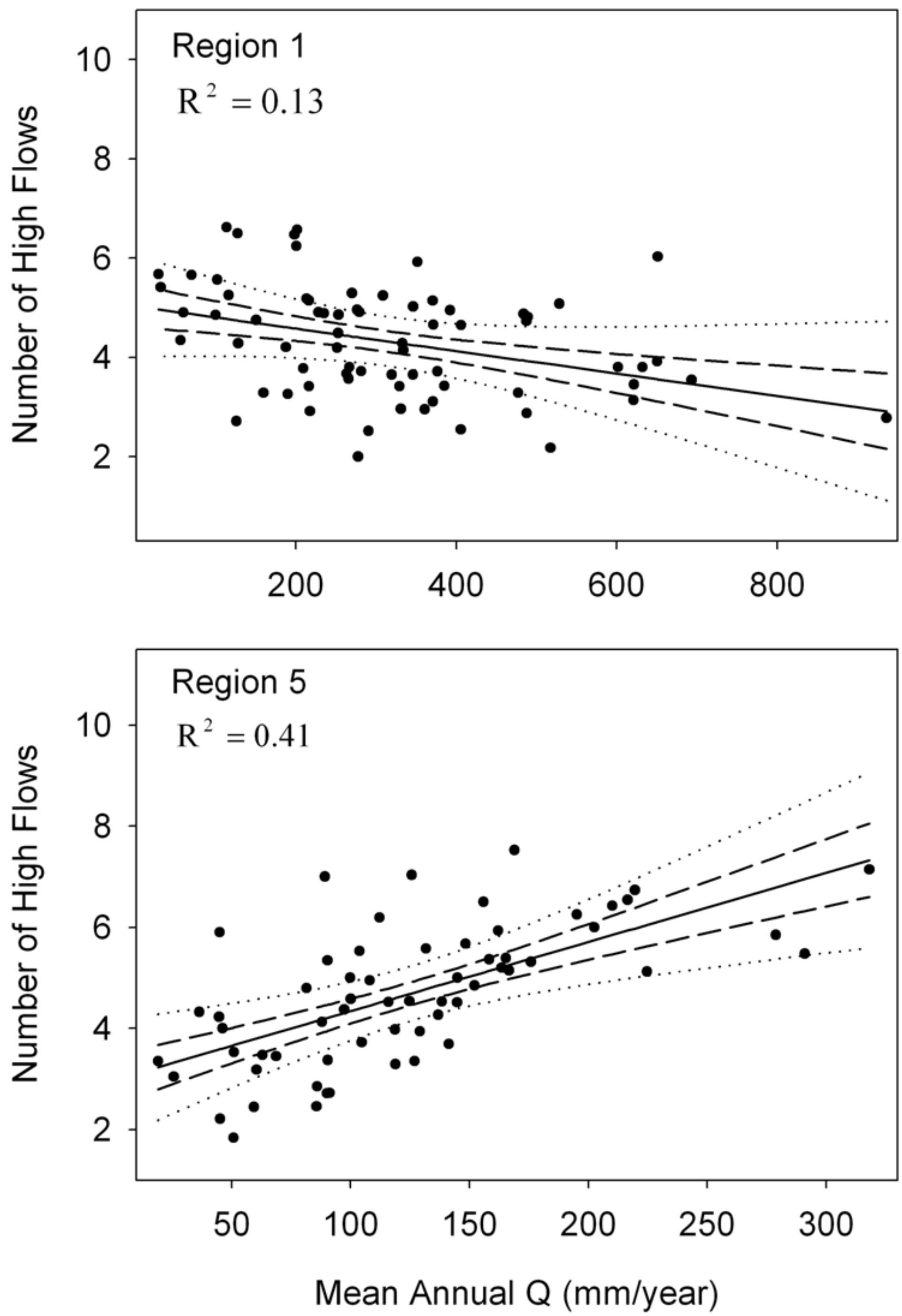


Figure 4-8 Relationship between the number of discrete low flows and the change in mean annual regional streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression (α = 0.05). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

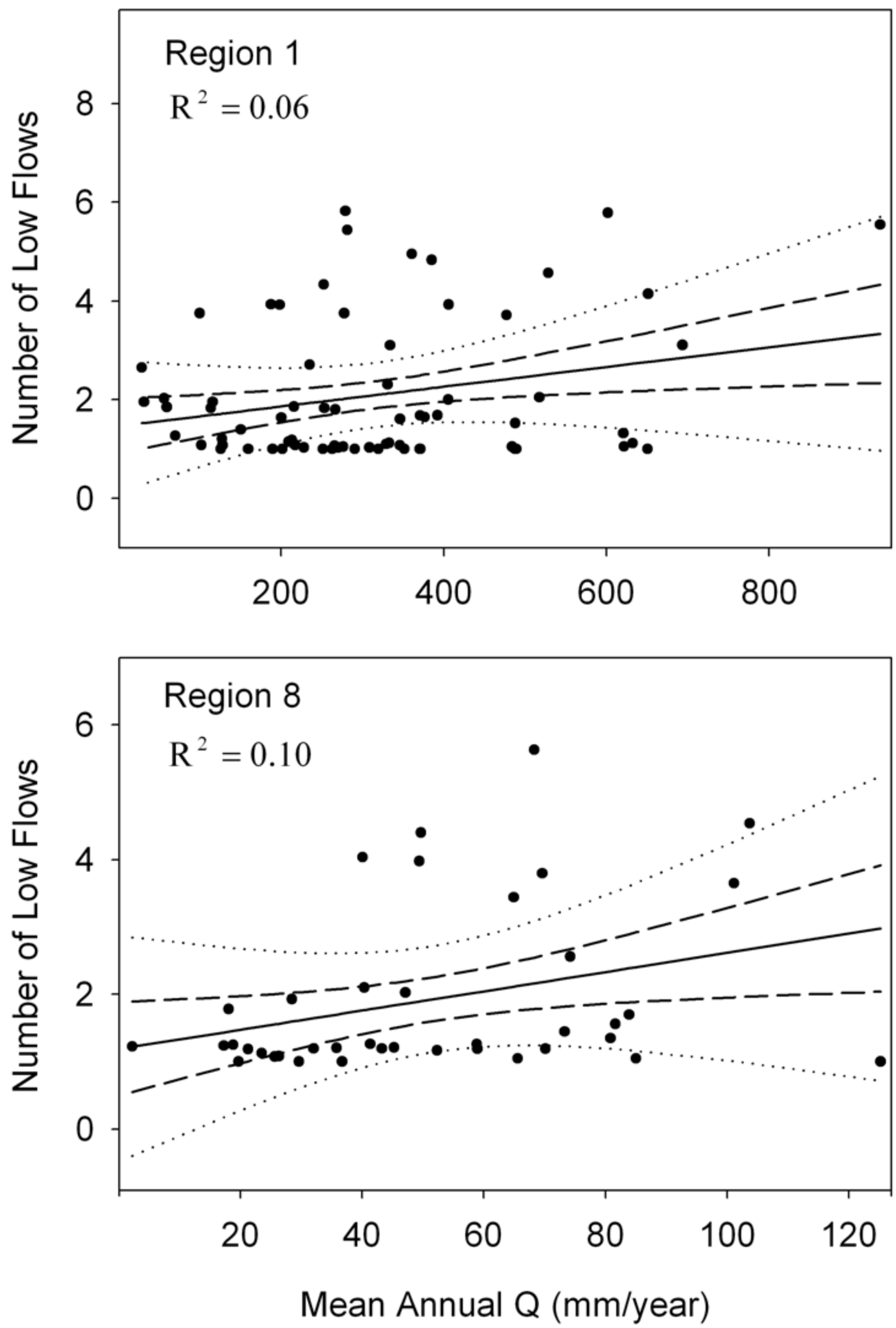


Figure 4-9 Relationship between the number of discrete seasonal low flows and the change in mean regional annual streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression ($\alpha = 0.05$). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.

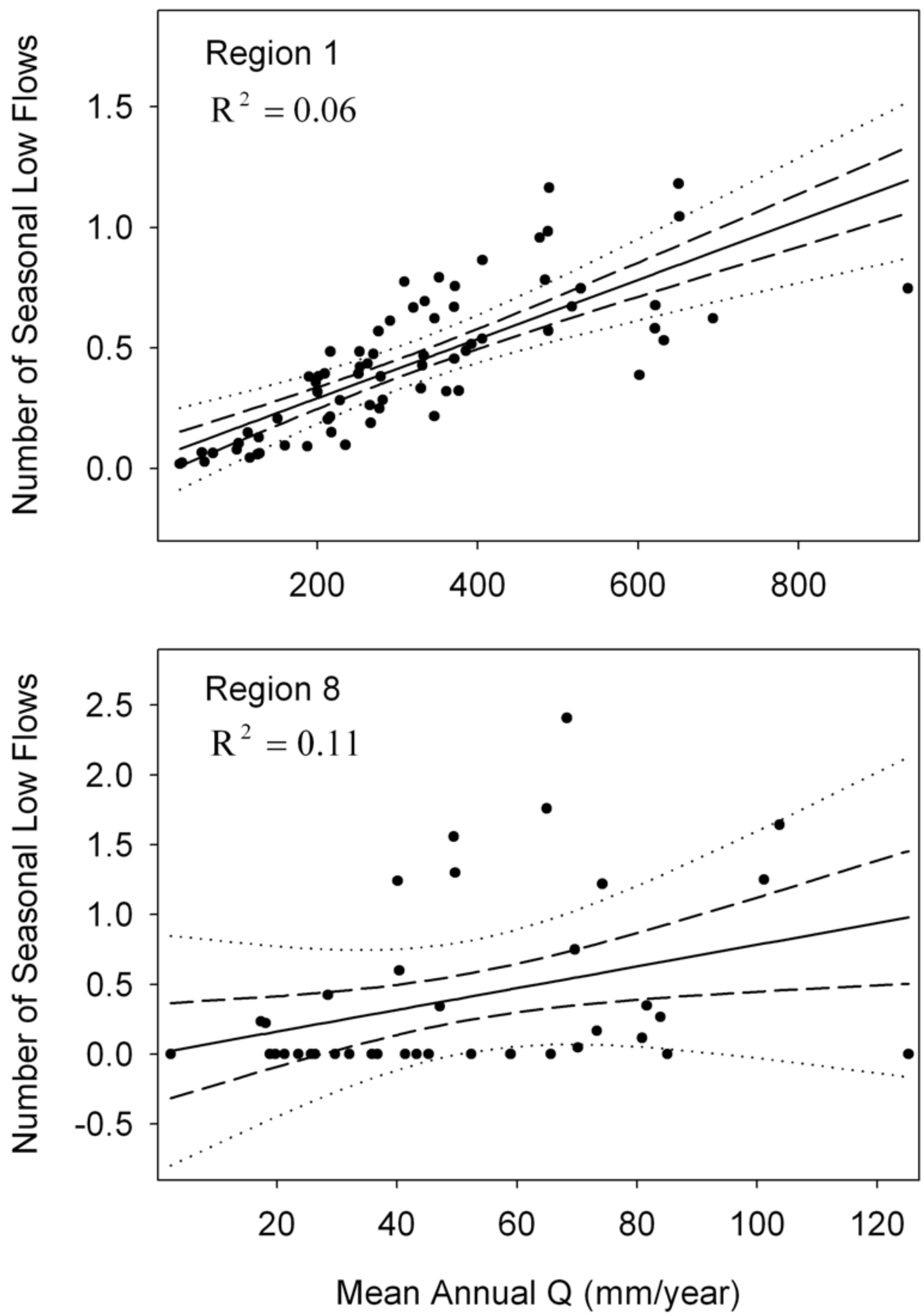
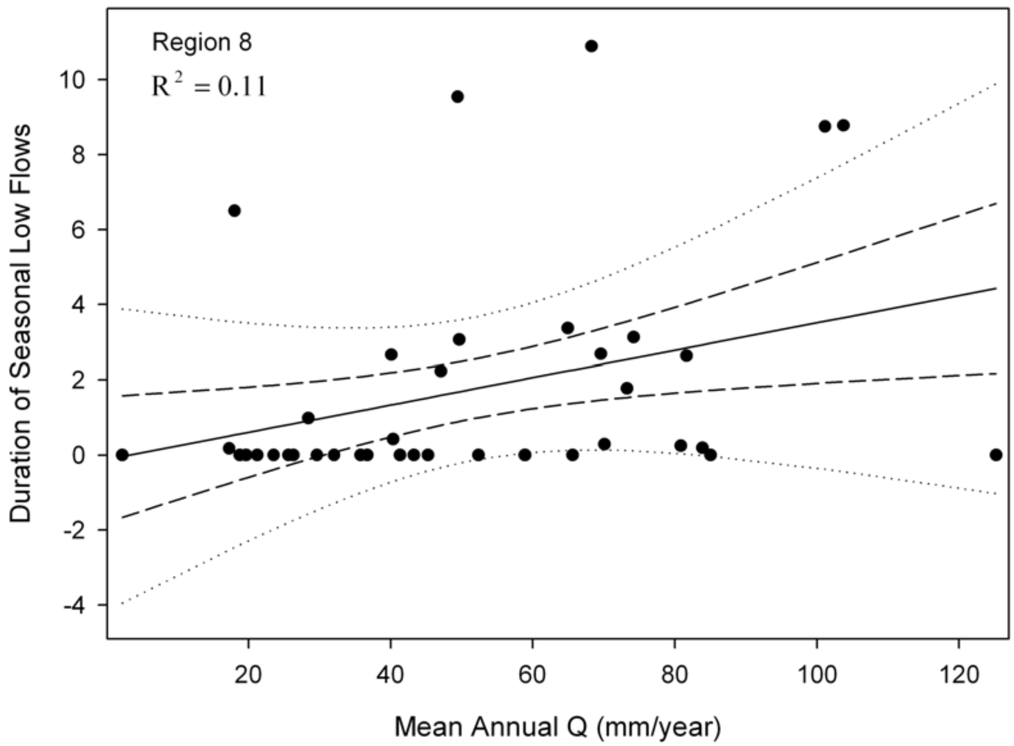


Figure 4-10 Relationship between the duration of discrete seasonal low flows and mean annual regional streamflow (mm/year) for hydrologic regions that were found to be significant by linear regression ($\alpha = 0.05$). Solid line denotes line of best fit; dashed lines closest to best fit line are the 80% confidence interval with outer dashed line denoting the 95% confidence interval.



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Chapter 5: Synthesis

The broad objectives of this research were to (1) classify the province's forested landbase into hydrologic regions using long term streamflow records, (2) to explore the physiographic characteristics of study catchments thought to be influencing hydrologic behaviour, and (3) determine the historic range of natural variation in a number of hydrologic parameters across Alberta's green zone. The overarching goal of these three objectives was aimed at development of a hydrologic risk assessment framework to enable a more accurate evaluation of the projected impacts of forest disturbance on streamflows and other hydrologic indicators for the forested landbase of Alberta. These objectives are intended to support the development and evaluation of forest management plans (FMP) across Alberta's forested landbase.

5.1 Hydrologic classification of Alberta's forested regions

The first study (chapter two) tested a hydrologic classification approach using the standardized shape factor of the mean annual surface water hydrograph to group catchments into regions with similar streamflow regimes. This classification approach was evaluated to determine if hydrograph shape factor captured regional differences in a broad set of independently calculated hydrologic variables representative of the overall streamflow regime. By evaluating the validity of a hydrograph shape factor based classification approach, the use of mean annual hydrographs as a powerful and parsimonious approach to hydrologic classification was supported.

Results from this study demonstrated that a hydrologic classification approach based on the standardized hydrograph shape factor was effective at highlighting the spatial variation in streamflow regimes. Three major groups were found within the forested regions of the province and three groups were found outside (within 80 kilometres) of the forested landbase. Each of the six regions showed distinct differences in hydrograph shape and although differences in magnitude were observed within groups, a general gradient in regional mean annual streamflows (from west to east) was observed. During the classification process, patterns in the variability of hydrographs (represented by the sequence in which groups were formed) became evident, with strongest differences being observed between the forested and non-forested landbase of the province; highlighting differences in the hydrologic behaviour between land use zones in the province. Although the hydrograph was divided into 18, 21 day temporal periods (variables) for classification, further analysis showed that only 4 temporal periods spanning March through June, representing the onset of spring snowmelt and the peak of the annual hydrograph, were most influential in differentiating hydrographs between regions. This demonstrated that the timing of spring snowmelt is a major component influencing differences in hydrologic characteristics between catchments across Alberta.

To test the classification technique and explore the representativeness (parsimony) of hydrograph shape factor; differences in 36 hydrologic parameters describing flow magnitudes, timing, frequencies, and flow durations were explored among regions. Results showed the presence of strong spatial gradients in most streamflow variables. Spatial patterns in streamflow characteristics were observed from west (the northern Rocky Mountains) to east (the Boreal plain). Larger streamflow magnitudes (high, average and low flows) and later calendar dates of streamflow timing (high, half annual and low flow dates) were observed in western regions when compared to eastern regions. Analysis of streamflow durations showed that high flow events were typically less variable and shorter in duration for western regions and more variable and longer in duration for eastern regions. Streamflow variables related to timing and magnitudes showed the largest differences between regions and accounted for the most of the variation across the forested landbase of the province; highlighting the spatial pattern of climatic variability present across the province. Results from this chapter demonstrated that a classification framework based on hydrograph shape factor captured spatial patterns in streamflow regimes at a landscape level scale while incorporating valuable hydrometric information important to water resource and land managers. This classification approach addressed the present ambiguity surrounding the appropriate selection of hydrologic (and physiographic) indices for use in classification frameworks and is the fundamental starting point in helping to understand the observed differences in hydrologic variability across the province of Alberta.

5.2 Physiographic and land cover characteristics of Alberta's forested regions

Objectives for the second study in this thesis (chapter three) were to characterize the regional variation in catchment physiography and land cover classes and to examine the covariance between the physiographic and hydrometric characteristics across hydrologic regions. These objectives provided insights into the fundamental controls regulating streamflow response across the forested landbase of Alberta.

Results showed the largest physiographic differences were present between the 3 forested regions. Strong spatial gradients in elevation, slope and descriptors of topographic variability contributed most to regional differences. Differences in land cover were also pronounced with westerly regions having greater proportions of forest, ice, snow and rock cover and easterly regions having less forest cover, more herbaceous land (e.g. crops) and greater proportions of wetlands. The patterns of spatial variability in catchment characteristics were complemented by spatial patterns in hydrologic variables describing the overall flow regime. Both physical and hydrologic descriptors followed a similar gradient suggesting that, at the scale of this study, differences in streamflow regimes are being driven by variation in topography and topographic controls on climate (e.g. orographic processes) and that the variability of landscape characteristics are reflected in similar gradients of hydrology variability. Results from correlation analysis of catchment characteristics to hydrologic characteristics showed strong associations between catchment physiography, streamflow magnitudes and streamflow timing. Hydrologic variables related to streamflow magnitudes co-varied the greatest with elevation, relief, and solar radiation. Western regions were characterized by higher elevations and solar radiation, steeper slopes and greater relief and also had streamflows of larger magnitudes with later timing. Easterly regions were characterized by catchments with lower elevations, more gradual relief and slopes and had streamflows of smaller magnitudes and earlier timing.

The findings from this study support that a classification framework based on hydrometric data can identify differences in physiographic controls at larger scales although physiography was not initially considered in the classification process. Additionally, results showed that at the provincial scale, topography was one of the more influential controls determining regional hydrologic differences. At finer spatial scales and in areas of low relief, such as the Boreal plain of Alberta, the influence of geology and soils may exert a greater role than topography in influencing catchment hydrology and streamflow, emphasized in research by Devito *et al.* (2005). The research in chapter three demonstrated the importance of using hydrometric data as the principal approach for hydrologic classification. If a landscape based approach to classification would have been used, the classification framework would have been limited by *a priori* selection of variables for classification inputs and insights into the hydrologic variability across Alberta's forested regions would have been constrained by physiographic controls (e.g. Golder, 2006; *unpublished*). The most informative method to classify hydrologic regions is based on streamflow with the subsequent analysis of regional physiography complimenting our understanding of why regional differences in hydrologic behaviour are present.

5.3 Hydrologic risk assessment framework for Alberta's forested regions

The broad objectives of chapter 4 were to define the natural range of variation (NRV) of hydrologic variables considered to be important from an ecological, societal and water resource management perspective (e.g. those which could be used for criteria and indicators to asses sustainable forest management practices for water resources) and to determine how disturbance (e.g. forest harvest) impacted the regional magnitude, timing, frequency and duration of streamflows. This chapter was presented as a case study to provide guidance for evaluating hydrologic change as a result of planned forest management activities based on a risk assessment framework for the forested landbase of Alberta. The case study focused on quantifying the risk (by using confidence intervals) of exceeding the NRV associated with increasing levels of forest harvest within a watershed. This analysis allowed the exploration of potential thresholds for each hydrologic variable's NRV based on the modeled changes to annual water yields.

The results of this study highlighted the large differences in the natural range of hydrologic variation between regions across the forested landbase of Alberta. Within each hydrologic region, different levels of hydrologic sensitivity were observed using the ECA Alberta model (Silins, 2002). Regions located in the higher elevation Rocky Mountains showed the lowest level of hydrologic sensitivity to forest disturbance, whereas regions spanning the lower foothills and Boreal forest of Alberta showed a greater level of hydrologic sensitivity to forest harvesting scenarios. Regions located in the non-forested landbase showed the greatest hydrologic sensitivity to forest harvesting scenarios. It is likely that the differential levels of sensitivity between hydrologic regions can be attributed to regional runoff ratios, which are a combined result of climatic and physiographic controls and their interaction amongst each other (e.g. differences in hydrologic gradients, storage capacity and conditions of evaporative demand).

The application of these results into a risk analysis framework suggests that the risk of exceeding the hydrologic NRV from forest disturbance is regionally dependant. This risk assessment framework will allow forest managers to quantify the projected hydrologic impacts of forest management plans and help in the evaluation of potential tradeoffs related to specific management decisions for achieving the goals and objectives of an FMP. In this research, the identification of specific hydrologic criteria and indicators and specific management thresholds were not precisely defined for 2 reasons; (1) certain hydrologic indices will have greater emphasis on FMP decisions and the choice of hydrologic indices will depend on specific management goals, objectives, and regional issues of concern. (2) By providing the results in the form of an interactive risk assessment framework the hydrologic NRV can be evaluated in context of regional water resource values while still allowing flexibility for making management decisions.

5.4 Future research

Although this research provided a scientifically sound classification scheme for categorizing hydrologic variability across Alberta's forested regions, revealed dominant higher order controls that were influencing hydrologic variability, defined the natural range of variation in regional hydrologic characteristics and applied these findings in a forest management context; it is also important to consider how this research could be improved and address some unanswered questions.

Increase the number of hydrologic variables and introduce specific variables related to the hydrology of northern climates.

The 36 hydrologic variables that were calculated in chapter one and used for analysis in subsequent chapters were selected based on their potential sensitivity to change from natural or anthropogenic disturbance and from research guiding the selection of hydro-ecological indices (Richter *et al.*, 1996; Olden and Poff, 2003). The calculation of these hydrologic variables was a long and arduous process, which could have been much simpler if commercial software had been used for the calculation of hydrological variables (e.g. Nature Conservancy, 2009; Indicators of Hydrologic Alteration, Version 7.1). The IHA software calculates 67 statistical hydrologic parameters and provides a statistical interface for parametric and non-parametric analysis of hydrometric data to detect deviations from a 'normal' or 'baseline' condition (e.g. before/after comparisons of the hydrologic implications to streamflow regimes) (Richter *et al.*, 1996). However, by calculating hydrologic variables independently of a computer program, it was the author's intent to make this research a more fruitful experience and to develop the additional skills in statistical hydrology. However, this highlighted some important issues in how various hydrologic parameters are defined including clear variation in definition of these parameters across the research literature (e.g. peakflows or high flows). This limited my ability to directly compare my results with that of others. Another potential downfall of manually calculating hydrologic variables is that there was difficulty in applying findings to other research that used alternate calculation methods (e.g. IHA software). However, a great deal of knowledge was gained from manual calculations during this research and although variables were calculated and defined differently, they were adequately representative of hydrologic variables calculated elsewhere. The author also notes that there is a need for incorporating additional hydrologic variables that could be considered as critical to water resources management in northern climates. For example, hydrologic variables related to the timing of fall freeze-up conditions and spring break-up conditions would provide a great deal of information on river ice regimes and may be important ecological indicators in northern climates or help indicate shifts in streamflow regimes due to climate change issues.

Incorporate more hydrometric stations/catchments in classification and statistical analysis.

If a larger number of hydrometric stations were used in the analysis a more accurate representation of the spatial boundaries of catchments with common hydrologic behaviour might have been achieved. This is balanced by the original criteria used to select hydrometric data and study watersheds. If compromises would have been made in regards to data record length or the quality of hydrometric data, the introduced variance from poor hydrometric records may have confounded results. This issue is unresolved; however, further analysis using multivariate discriminant analysis techniques could allocate 'new' catchments with less complete hydrometric records into the current classification frameworks and provide a quantitative measure of the potential error associated with the new classification (e.g. misclassification rate) (Dillon and Goldstein, 1984).

Test classification technique using additional classification methods

Truly, to call a classification scheme or approach "robust" multiple classification techniques should be tested using identical data sets to determine if the final solution is statistically valid. Incorporating additional cluster techniques such as k-means clustering could be used to ensure that hierarchically based cluster algorithms accurately captured and grouped the variability of hydrograph shapes into homogeneous regions. However, the delineation of regions in this study corresponded closely to other classification approaches applied in the province of Alberta (Golder, 2006; *unpublished*) and results corresponded positively to hypothesised provincial hydro-climatic boundaries. This suggests that results from this study are representative of the hydrologic variation across the forested regions of the province and adequately captured differences in hydrologic characteristics at a landscape level scale.

Include additional physiographic variables

To create a classification framework that can be generalized to areas where hydrometric data may not be readily available, more linkages to the physical hydrologic controls of the catchment are needed. This research explored only a few physiographic characteristics of catchments to develop relationships between physical and hydrologic characteristics within and between regions. To increase understanding and develop connections between landscape and streamflow based classification approaches a greater number of physiographic characteristics should be used. Measures directly related to stream morphology and geomorphology such as stream slope, bifurcation ration, sinuosity, bed form, channel gradient, and entrenchment ratio could be included. Augmenting the number of variables that describe both hydrologic characteristics and physical catchment characteristics will greatly improve any type of hydrologic classification approach. By using newer statistical methods (e.g. Multivariate Regression Tree Analysis [MRT]) (De'ath and Fabricius, 2000; De'ath, 2002) that are not reliant on parametric assumptions and which test the relative influence of input parameters on classification results, our ability to visualize patterns in streamflow and dominant hydrologic controls would be improved.

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Appendices

Appendix 2-1 List of Water Survey of Canada (WSC) hydrometric stations selected for hydrologic classification and analysis. Table columns show WSC station number, WSC station name, watershed area (km^2), geographic location (latitude and longitude in degrees minutes seconds), landbase (WZ = White Zone; GZ = Green Zone; NP = National Park), WSC record length, and WSC operational status at the time of data collection (D = Discontinued; O = Operational).

Station Number	Station Name	Area (km2)	Latitude (degrees)	longitude (degrees)	Land Base	Record Length	Status
07BJ004	ADAMS CK NEAR KINUSO	139	55 13 04	-115 20 01	WZ	18	D
05EA009	ATIM CK NEAR SPRUCE GROVE	285	53 34 56	-113 54 40	WZ	29	O
05ED002	ATIMOSWE CK NEAR ELK POINT	368	53 53 20	-110 55 19	WZ	32	O
07CA008	BABETTE CK NEAR COLINTON	219	54 39 10	-113 04 52	WZ	33	O
05DC012	BAPTISTE RVR NEAR THE MOUTH	1346	52 39 51	-115 04 36	GZ	23	O
05FA001	BATTLE RVR NEAR PONOKA	1827	52 39 33	-113 36 15	WZ	95	O
07GE007	BEAR CK NEAR VALHALLA CENTRE	183	55 24 02	-119 23 02	WZ	23	O
05CA011	BEARBERRY CK NEAR SUNDRE	227	51 48 26	-114 42 41	WZ	31	O
05AB013	BEAVER CK NEAR BROCKET	256	49 38 21	-113 47 51	WZ	87	D
07DA018	BEAVER RVR ABOVE SYNCRUDE	165	56 56 29	-111 34 03	GZ	32	D
05CB005	BEAVERDAM CK NEAR COCHRANE	46	51 21 46	-114 26 31	WZ	15	D
07GD001	BEAVERLODGE RVR NEAR BEAVERLODGE	1609	55 11 23	-119 26 24	WZ	39	D
07GD002	BEAVERTAIL CK NEAR HYTHE	666	55 18 54	-119 38 26	WZ	25	D
07NB006	BENCH MARK CK NEAR FORT SMITH	66	59 47 59	-111 57 11	NP	17	D
07CE006	BIRCH CK NEAR CONKLIN	232	55 37 03	-111 05 20	GZ	11	D
05CC001	BLINDMAN RVR NEAR BLACKFALDS	1795	52 21 23	-113 47 33	WZ	95	D
05CC010	BLOCK CK NEAR LEEDALE	53	52 34 12	-114 36 10	WZ	31	O
05BA001	BOW RVR AT LAKE LOUISE	422	51 25 44	-116 11 21	NP	97	D
07JF004	BOYER RVR NEAR PADDLE PRAIRIE	94	57 54 29	-117 36 55	WZ	28	O
05BB004	BREWSTER CK NEAR BANFF	110	51 05 58	-115 40 01	NP	26	D
07GF005	BRIDLEBIT CK NEAR VALLEYVIEW	21	54 56 12	-117 44 04	WZ	40	O
05DD004	BROWN CK AT FORESTRY ROAD	219	52 45 47	-116 21 50	GZ	92	D
07HC002	BUCHANAN CK NEAR MANNING	232	56 53 44	-117 29 23	WZ	22	O
05BF019	CABIN CK NEAR SEEBE	2	50 57 38	-115 10 02	GZ	23	D
07AD003	CACHE PERCOTTE CK NEAR HINTON	7	53 24 04	-117 30 30	GZ	12	D
07HB001	CADOTTE RVR AT THE OUTLET OF CADOTTE LK	879	56 29 10	-116 26 04	GZ	23	O
05DD008	CARDINAL RVR NEAR THE MOUTH	493	52 52 10	-116 35 60	GZ	28	D
05BD005	CASCADE RVR ABOVE LAKE MINNEWANKA	452	51 17 16	-115 32 08	NP	23	D
05AA028	CASTLE RVR AT RANGER STATION	375	49 23 57	-114 20 20	GZ	40	O
05AA022	CASTLE RVR NEAR BEAVER MINES	821	49 29 25	-114 08 50	WZ	62	D
05BL022	CATARACT CK NEAR FORESTRY ROAD	165	50 17 04	-114 35 29	GZ	41	D
07AH002	CHRISTMAS CK NEAR BLUE RIDGE	423	54 13 39	-115 20 05	GZ	35	O
05DB003	CLEARWATER RVR ABOVE LIMESTONE CK	1343	51 59 44	-115 26 11	GZ	33	D
07GE006	COLQUHOUN CK NEAR GRANDE PRAIRIE	128	55 17 15	-119 08 54	WZ	13	D
07BB009	CONNOR CK NEAR SANGUDO	165	54 01 24	-114 56 48	WZ	35	O

Station Number	Station Name	Area (km2)	Latitude (degrees)	longitude (degrees)	Land Base	Record Length	Status
07BB014	COYOTE CK NEAR CHERHILL	49	53 52 22	-114 40 10	WZ	26	O
05AA008	CROWSNEST RVR AT FRANK	401	49 36 19	-114 24 44	WZ	97	D
07GB001	CUTBANK RVR NEAR GRANDE PRAIRIE	839	54 31 15	-118 59 42	GZ	37	O
07BC006	DAPP CK AT HIGHWAY NO. 44	605	54 18 28	-113 50 56	WZ	35	O
07GF008	DEEP VALLEY CK NEAR VALLEYVIEW	635	54 25 43	-117 43 11	GZ	22	O
05CA003	DEER CK (MAIN STEM) NEAR SUNDRE	6	51 39 34	-115 08 04	GZ	29	D
07AF004	DEERLICK CK NEAR HINTON	14	53 09 14	-117 14 37	GZ	25	D
07BH003	DRIFTPILE RVR NEAR DRIFTPILE	838	55 20 42	-115 47 51	WZ	14	D
05AD016	DRYWOOD CK NEAR TWIN BUTTE	31	49 18 05	-114 00 23	WZ	51	D
05AA026	DUTCH CK NEAR THE MOUTH	143	49 54 09	-114 26 59	GZ	29	D
07BF001	EAST PRAIRIE RVR NEAR ENILDA	1467	55 25 03	-116 20 22	WZ	92	D
05AB024	EAST STREETER CK NEAR NANTON	1	50 06 29	-114 02 58	GZ	10	D
05BJ006	ELBOW RVR ABOVE ELBOW FALLS	438	50 51 20	-114 47 36	GZ	28	D
05BJ004	ELBOW RVR AT BRAGG CK	791	50 56 57	-114 34 06	WZ	84	D
05BJ010	ELBOW RVR AT SARCEE BRIDGE	1189	50 59 45	-114 09 55	WZ	28	O
07HB002	ELDER CK AT HIGHWAY NO. 686	64	56 27 48	-116 49 54	GZ	10	D
07AF014	EMBARRAS RVR NEAR WEALD	640	53 22 28	-116 48 29	GZ	23	O
07AF005	EUNICE CK NEAR HINTON	16	53 09 05	-117 13 52	GZ	26	D
07FD013	EUREKA RVR NEAR WORSLEY	755	56 27 07	-119 07 59	WZ	32	O
05CA012	FALLENTIMBER CK NEAR SUNDRE	489	51 44 09	-114 39 15	WZ	31	O
05BK001	FISH CK NEAR PRIDDIS	261	50 53 09	-114 19 41	WZ	100	D
07CA003	FLAT CK NEAR BOYLE	184	54 35 11	-112 54 26	WZ	88	O
05BB003	FORTY MILE CK NEAR BANFF	133	51 12 25	-115 35 10	NP	67	D
07AH001	FREEMAN RVR NEAR FORT ASSINIBOINE	1662	54 21 54	-114 54 25	WZ	42	D
05AD904	GALWEY BROOK NEAR WATERTON PARK	20	49 08 12	-113 51 13	WZ	25	O
05BG002	GHOST RVR NEAR BLACK ROCK MOUNTAIN	210	51 18 19	-115 10 44	GZ	52	D
05AA030	GOLD CK NEAR FRANK	63	49 35 58	-114 24 07	WZ	100	D
07GE003	GRANDE PRAIRIE CK NEAR SEXSMITH	140	55 22 32	-118 54 52	WZ	38	O
07AF015	GREGG RVR NEAR THE MOUTH	384	53 15 09	-117 21 39	GZ	21	O
07AG008	GROAT CK NEAR WHITECOURT	132	54 01 59	-115 50 35	WZ	23	O
07CD004	HANGINGSTONE RVR AT FORT MCMURRAY	962	56 42 33	-111 21 26	GZ	42	O
07DA009	HARTLEY CK NEAR FORT MACKAY	359	57 15 33	-111 27 55	GZ	19	D
07HA003	HEART RVR NEAR NAMPA	1968	56 03 21	-117 07 39	WZ	44	D
05BL019	HIGHWOOD RVR AT DIEBEL'S RANCH	774	50 24 19	-114 29 56	WZ	57	O
05BL021	HIGHWOOD RVR BELOW PICKLEJAR CK	132	50 29 57	-114 49 09	GZ	20	D
07FD008	HINES CK NEAR FAIRVIEW	1247	56 04 09	-118 39 49	WZ	20	D
07GF007	HORSE CK NEAR VALLEYVIEW	4	54 55 23	-117 48 59	WZ	17	D
07CB002	HOUSE RVR AT HIGHWAY NO. 63	781	55 38 31	-112 09 03	GZ	25	O
07GG003	IOSEGUN RVR NEAR LITTLE SMOKY	1954	54 44 42	-117 09 09	WZ	38	O
06AC001	JACKFISH CK NEAR LA COREY	492	54 26 33	-110 41 09	WZ	36	D
07CE005	JACKFISH RVR BELOW CHRISTINA LAKE	1289	55 40 21	-111 05 57	GZ	13	D
07JD003	JACKPINE CK AT WADLIN LAKE ROAD	582	58 11 31	-115 44 60	WZ	36	O
05CA002	JAMES RVR NEAR SUNDRE	821	51 55 36	-114 41 11	WZ	41	D
05BA006	JOHNSTON CK NEAR THE MOUTH	123	51 14 44	-115 50 28	NP	23	D

Station Number	Station Name	Area (km2)	Latitude (degrees)	longitude (degrees)	Land Base	Record Length	Status
07DA016	JOSLYN CK NEAR FORT MACKAY	255	57 16 27	-111 44 38	GZ	18	D
05BH013	JUMPINGPOUND CK NEAR COX HILL	37	51 00 02	-114 56 27	GZ	31	O
05BH009	JUMPINGPOUND CK NEAR THE MOUTH	571	51 09 15	-114 31 44	WZ	41	D
07HF002	KEG RVR AT HIGHWAY NO. 35	666	57 44 44	-117 37 38	WZ	36	D
07HA902	KRAWCHUK DRAINAGE NEAR MCLENNAN	13	55 57 14	-117 01 38	WZ	11	D
07JC001	LAFOND CK NEAR RED EARTH CK	492	57 04 22	-115 05 56	GZ	32	O
07GJ005	LALBY CK NEAR GIROUXVILLE	159	55 47 31	-117 20 11	WZ	18	D
05AE040	LEE CK (EAST BRANCH) NEAR BEAZER	40	49 00 59	-113 32 29	WZ	15	D
05AE037	LEE CK AT BEAZER	180	49 06 56	-113 29 08	WZ	15	D
05AE904	LEE CK BELOW CONFLUENCE OF EAST FORK	94	49 01 01	-113 32 25	WZ	11	D
07BG004	LILY CK NEAR SLAVE LAKE	24	55 24 58	-114 48 48	GZ	20	O
07AC008	LITTLE BERLAND RVR AT HIGHWAY NO. 40	93	53 40 40	-118 14 32	GZ	21	O
05BJ009	LITTLE ELBOW RVR ABOVE NIHAHI CK	130	50 47 42	-114 55 06	GZ	17	D
07BB005	LITTLE PADDLE RVR NEAR MAYERTHORPE	295	53 57 53	-115 10 37	WZ	44	O
05CB002	LITTLE RED DEER RVR NEAR WATER VALLEY	451	51 30 39	-114 40 23	WZ	46	O
05CC009	LLOYD CK NEAR BLUFFTON	239	52 44 25	-114 08 42	WZ	42	O
07BB003	LOBSTICK RVR NEAR STYAL	1575	53 36 45	-115 06 32	WZ	32	D
07CA012	LOGAN RVR NEAR THE MOUTH	428	55 10 45	-111 43 43	GZ	23	O
07BA003	LOVETT RVR NEAR THE MOUTH	99	53 00 60	-116 40 20	GZ	33	D
07OB006	LUTOSE CK NEAR STEEN RVR	292	59 24 22	-117 16 55	GZ	30	O
07DB005	MACKAY RVR ABOVE DUNKIRK RVR	1015	56 45 39	-112 36 57	GZ	10	D
07AA004	MALIGNE RVR NEAR JASPER	899	52 55 49	-118 01 34	NP	94	D
05BF016	MARMOT CK MAIN STEM NEAR SEEBE	9	50 57 03	-115 09 12	GZ	45	O
05FA014	MASKWA CK NO. 1 ABOVE BEARHILLS LAKE	79	52 47 05	-113 37 46	WZ	35	D
05AA013	MCGILLIVRAY CK NEAR COLEMAN	32	49 38 10	-114 31 16	WZ	79	D
07AF013	MCLEOD RVR NEAR CADOMIN	330	53 04 47	-117 11 53	GZ	23	O
05AB029	MEADOW CK NEAR THE MOUTH	130	49 57 11	-113 39 51	WZ	41	O
07OB005	MEANDER RVR AT OUTLET OF HUTCH LAKE	506	58 46 18	-117 22 22	GZ	20	D
05CC007	MEDICINE RVR NEAR ECKVILLE	1916	52 19 13	-114 20 41	WZ	45	O
05BF020	MIDDLE FORK CK IN CIRQUE NEAR SEEBE	1	50 57 30	-115 12 00	GZ	22	D
05BF017	MIDDLE FORK CK NEAR SEEBE	3	50 57 37	-115 10 26	GZ	23	D
07AA001	MIETTE RVR NEAR JASPER	629	52 51 47	-118 06 40	NP	94	D
05AA011	MILL CK NEAR THE MOUTH	179	49 27 56	-114 08 07	WZ	101	D
05DA007	MISTAYA RVR NEAR SASK CROSSING	248	51 53 00	-116 41 19	NP	57	D
07FD012	MONTAGNEUSE RVR NEAR HINES CK	228	56 23 05	-118 42 39	WZ	32	O
05ED003	MOOSEHILLS CK NEAR ELK POINT	41	53 56 02	-110 46 36	WZ	29	O
07DA008	MUSKEG RVR NEAR FORT MACKAY	1457	57 11 34	-111 34 16	GZ	33	D
07GA002	MUSKEG RVR NEAR GRANDE CACHE	703	53 55 32	-118 48 52	GZ	36	D
05DD009	NORDEGG RVR AT SUNCHILD ROAD	876	52 49 12	-115 30 55	GZ	36	O
05DC011	NORTH RAM RVR AT FORESTRY ROAD	347	52 16 59	-115 59 60	GZ	32	O
05DA006	NORTH SASK RVR AT SASK CROSSING	1287	51 58 02	-116 43 33	NP	20	D
05DA009	NORTH SASK RVR AT WHIRLPOOL POINT	1923	52 00 06	-116 28 22	GZ	37	O
05BH003	NOSE CK AT CALGARY	886	51 07 20	-114 02 52	WZ	75	D
05AA023	OLDMAN RVR NEAR WALDRON'S CORNER	1446	49 48 54	-114 11 03	WZ	58	O

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07BB011	PADDLE RVR NEAR ANSELMO	253	53 51 35	-115 21 57	WZ	27	O
07GH004	PEAVINE CK NEAR FALHER	540	55 37 44	-117 15 30	WZ	23	O
05BL023	PEKISKO CK NEAR LONGVIEW	232	50 28 23	-114 12 28	WZ	41	O
05DA008	PEYTO CK AT PEYTO GLACIER	23	51 41 37	-116 32 12	NP	10	D
05FA019	PIGEON LAKE CK NEAR USONA	377	52 52 13	-113 53 53	WZ	17	D
05AA004	PINCHER CK AT PINCHER CK	157	49 29 13	-113 56 56	WZ	101	D
07CA005	PINE CK NEAR GRASSLAND	1456	54 49 10	-112 46 39	WZ	41	O
07GC002	PINTO CK NEAR GRANDE PRAIRIE	494	54 50 32	-119 23 23	GZ	21	O
07CE003	PONY CK NEAR CHARD	279	55 52 13	-110 55 03	GZ	25	O
07BE003	PORTER CK ABOVE BAPTISTE LAKE	57	54 43 29	-113 34 33	WZ	27	O
05AE011	POTHOLE CK NEAR MAGRATH	372	49 22 37	-112 53 25	WZ	37	D
05AD035	PRAIRIE BLOOD COULEE NEAR LETHBRIDGE	226	49 33 57	-112 57 23	WZ	37	O
05DB005	PRAIRIE CK BELOW LICK CK	208	52 15 18	-115 17 21	GZ	34	O
05DB002	PRAIRIE CK NEAR ROCKY MOUNTAIN HOUSE	844	52 16 22	-114 55 51	WZ	85	D
06AB003	PUNK CK NEAR THE MOUTH	395	54 32 18	-111 13 48	WZ	10	D
05AA027	RACEHORSE CK NEAR THE MOUTH	218	49 50 17	-114 25 14	GZ	41	O
05DC006	RAM RVR NEAR THE MOUTH	1854	52 22 04	-115 25 22	GZ	92	D
07BA002	RAT CK NEAR CYNTHIA	606	53 08 25	-115 29 22	GZ	36	D
05CB004	RAVEN RVR NEAR RAVEN	645	52 05 23	-114 28 42	WZ	36	O
05CE010	RAY CK NEAR INNISFAIL	44	52 00 05	-113 36 02	WZ	40	O
05CA004	RED DEER RVR ABOVE PANTHER RVR	941	51 39 35	-115 24 27	GZ	40	O
07JC002	REDEARTH CK NEAR RED EARTH CK	618	56 32 47	-115 14 27	GZ	20	O
05BB005	REDEARTH CK NEAR THE MOUTH	151	51 13 20	-115 48 47	NP	23	D
05EC007	REDWATER RVR NEAR VIMY	469	54 05 35	-113 33 60	WZ	10	D
07GD004	REDWILLOW RVR NEAR RIO GRANDE	1252	55 04 49	-119 42 13	WZ	14	O
06AD013	REITA CK NEAR OUTLET OF ANGLING LAKE	164	54 13 43	-110 19 51	WZ	10	D
07CE004	ROBERT CK NEAR ANZAC	54	56 22 59	-111 01 48	GZ	13	D
07GF006	ROCKY CK NEAR VALLEYVIEW	19	54 56 10	-117 46 44	WZ	40	D
05AE017	ROLPH CK AT VAUGHN RANCH	87	49 00 13	-113 09 39	WZ	10	D
05AE005	ROLPH CK NEAR KIMBALL	222	49 07 30	-113 08 30	WZ	96	D
07BB903	ROMEO CK ABOVE ROMEO LAKE	114	54 04 11	-114 54 07	WZ	20	D
05DE007	ROSE CK NEAR ALDER FLATS	559	52 55 50	-115 00 36	WZ	36	D
05CE006	ROSEBUD RVR BELOW CARSTAIRS CK	753	51 24 60	-113 43 41	WZ	50	O
07FD006	SADDLE RVR NEAR WOKING	540	55 38 40	-118 42 07	WZ	41	D
07AH003	SAKWATAMAU RVR NEAR WHITECOURT	1145	54 12 07	-115 46 53	GZ	35	O
07BF009	SALT CK NEAR GROUARD	427	55 36 33	-116 06 30	WZ	21	O
07BK009	SAWRIDGE CK NEAR SLAVE LAKE	235	55 17 02	-114 45 19	GZ	32	O
05CE019	SHEEP COULEE NEAR CARSTAIRS	39	51 33 47	-114 02 13	WZ	17	D
05BL014	SHEEP RVR AT BLACK DIAMOND	594	50 41 15	-114 14 38	WZ	99	O
05BL018	SHEEP RVR AT BUCK RANCH	454	50 37 21	-114 26 09	WZ	19	D
05BL012	SHEEP RVR AT OKOTOKS	1496	50 43 19	-113 58 60	WZ	99	D
07BC004	SHOAL CK NEAR LINARIA	442	54 18 51	-114 12 10	WZ	10	D
05DA002	SIFFLEUR RVR NEAR THE MOUTH	515	52 02 50	-116 23 21	GZ	81	D
05DA010	SILVERHORN CK NEAR THE MOUTH	21	51 47 57	-116 34 50	NP	36	O

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07AB002	SNAKE INDIAN RVR NEAR THE MOUTH	1587	53 09 35	-118 02 09	NP	26	D
07OA001	SOUSA CK NEAR HIGH LEVEL	820	58 35 13	-118 29 29	GZ	37	O
07GF004	SPRING CK (UPPER) NEAR VALLEYVIEW	34	54 55 44	-117 42 29	WZ	20	D
07GF002	SPRING CK NEAR VALLEYVIEW	118	54 55 04	-117 50 55	WZ	21	D
07DA006	STEEPBANK RVR NEAR FORT MCMURRY	1320	57 00 15	-111 24 59	GZ	35	D
07BE004	STONY CK NEAR TAWATINAW	128	54 17 33	-113 27 46	WZ	26	O
05DF004	STRAWBERRY CK NEAR THE MOUTH	592	53 18 39	-114 03 12	WZ	41	O
05AB030	STREETER CK (MAIN STEM) NEAR NANTON	6	50 07 22	-114 03 26	WZ	20	D
05EA010	STURGEON RVR NEAR MAGNOLIA BRIDGE	121	53 35 28	-114 51 42	WZ	26	O
07AF010	SUNDANCE CK NEAR BICKERDIKE	178	53 33 57	-116 42 17	GZ	35	O
07AA007	SUNWAPTA RVR AT ATHABASCA GLACIER	29	52 13 03	-117 14 07	NP	59	D
07BJ001	SWAN RVR NEAR KINUSO	1904	55 20 09	-115 24 56	WZ	92	D
07BJ003	SWAN RVR NEAR SWAN HILLS	155	54 48 18	-115 27 58	GZ	37	O
07JD004	TEPEE CK NEAR LA CRETE	135	58 08 14	-116 14 60	WZ	27	O
05CE018	THREEHILLS CK BELOW RAY CK	199	51 59 52	-113 34 10	WZ	36	O
05BL013	THREEPOINT CK NEAR MILLARVILLE	507	50 46 15	-114 16 46	WZ	99	D
05AA006	TODD CK AT ELTON'S RANCH	144	49 39 30	-114 07 41	WZ	85	D
05AA909	TODD CK NEAR HIGHWAY NO. 22	74	49 45 47	-114 14 08	WZ	25	O
05DE009	TOMAHAWK CK NEAR TOMAHAWK	95	53 24 20	-114 45 53	WZ	23	O
05AE039	TOUGH CK NEAR BEAZER	39	49 04 41	-113 32 21	WZ	38	O
05BL027	TRAPP CK NEAR LONGVIEW	137	50 28 38	-114 25 37	WZ	28	O
05AB005	TROUT CK NEAR GRANUM	441	49 58 38	-113 41 14	WZ	99	D
05BF018	TWIN CK NEAR SEEBE	3	50 57 32	-115 10 33	GZ	23	D
07DA011	UNNAMED CK NEAR FORT MACKAY	278	57 39 32	-111 31 05	GZ	18	D
05DE003	WABAMUN CK NEAR DUFFIELD	563	53 27 47	-114 22 03	WZ	68	D
07BC007	WABASH CK NEAR PIBROCH	344	54 13 28	-113 55 31	WZ	28	O
07BC003	WABASH CK NEAR WESTLOCK	326	54 11 33	-113 55 34	WZ	13	D
07FD014	WAINSCOTT COULEE NEAR BROWNVALE	150	56 01 40	-117 56 18	WZ	16	D
05BG009	WAIPAROUS CK BELOW MEADOW CK	229	51 22 05	-114 59 31	GZ	12	D
05BG006	WAIPAROUS CK NEAR THE MOUTH	333	51 17 01	-114 50 22	WZ	41	D
07AF003	WAMPUS CK NEAR HINTON	26	53 09 23	-117 15 43	GZ	41	O
07CA006	WANDERING RVR NEAR WANDERING RVR	1120	55 12 00	-112 28 06	WZ	36	D
07GG001	WASKAHIGAN RVR NEAR THE MOUTH	1037	54 45 05	-117 12 20	WZ	39	D
05AD003	WATERTON RVR NEAR WATERTON PARK	613	49 06 49	-113 50 25	NP	99	O
05BM018	WEST ARROWWOOD CK NEAR ENSIGN	30	50 30 48	-113 20 40	WZ	22	O
07BF002	WEST PRAIRIE RVR NEAR HIGH PRAIRIE	1152	55 26 49	-116 29 35	WZ	92	O
05DF007	WEST WHITEMUD CK NEAR IRETON	65	53 13 16	-113 41 30	WZ	31	O
07AA009	WHIRLPOOL RVR NEAR THE MOUTH	589	52 43 29	-117 55 34	NP	30	D
07AD004	WHISKEYJACK CK NEAR HINTON	3	53 22 49	-117 32 17	GZ	28	D
05EC006	WHITE EARTH CK NEAR SMOKY LAKE	1012	54 07 01	-112 18 05	WZ	10	D
07AC001	WILDHAY RVR NEAR HINTON	960	53 31 14	-117 57 08	GZ	42	O
05AB028	WILLOW CK ABOVE CHAIN LAKES	162	50 11 50	-114 12 49	WZ	30	D
05AB040	WILLOW CK AT SECONDARY 532	65	50 14 30	-114 21 16	GZ	11	O
07JA003	WILLOW RVR NEAR WABASCA	1038	55 54 48	-113 55 23	GZ	35	D

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07AG003	WOLF CK AT HIGHWAY NO. 16A	826	53 35 53	-116 16 23	WZ	52	O
06AB002	WOLF RVR AT OUTLET OF WOLF LAKE	726	54 42 44	-111 00 06	GZ	39	D
07GF003	WOLVERINE CK NEAR VALLEYVIEW	11	54 55 22	-117 48 39	WZ	20	D
07FD913	YOUNG DRAINAGE PROJECT NEAR SPIRIT RVR	31	55 48 57	-118 47 05	WZ	25	O