The Impact of Climate Change on Streamflow in the Blueberry River, Northern British Columbia, and the Potential Influence on Oil and Gas Development

Elliot McLauchlan

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Department of Earth Sciences,
Dalhousie University, Halifax, Nova Scotia
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Abstract-

Water withdrawal for oil and gas extraction and other uses has become common for highly seasonal streams in watersheds of northeastern British Columbia with the recent surge of unconventional resource development. Permissible withdrawals are administered that maintain the environmental flow needs of the stream. However, discharges may vary over the next 40-60 years, owing to climate change, which could influence the sustainability of current rates of withdrawal. To examine this problem, I focus on streamflow in the Blueberry River Basin in northeastern British Columbia (area 1,777 km^2). Streamflow in the Blueberry was modeled using the HBV-EC watershed model. The model was calibrated using gauge and climate data for 1978-1982. Simulations for 2046-2065 used daily and monthly climate data from the IPCC SRES A1B emission scenario, in the CGCM3.1/T47 Global Climate Model. Mean annual precipitation remained constant between the years 2046-65 and the calibration period, although there was moderate monthly variation. Mean annual snowfall increased by 0.03 cm and mean annual temperature rose by 1.51 ºC. Snowfall and temperature also experience monthly fluctuations. The initial spring freshet in the historic period typically occurred around April 29, while the timing of the simulated peak spring freshet was forecast earlier, changing from late April to late March. All years simulated showed an increase in late season discharge, with significant discharge commonly occurring in November months. Under current allocations in the Blueberry River, all simulated years would experience water shortages in January, February, and March, with the exception of March 2050. No simulated year predicted water shortages in December, or any non-winter month. I propose that changes to hydrology in the Blueberry River Basin are plausible in the next 50 years. The magnitude of these changes however, is difficult to predict with a high degree of certainty, due to some of the limitations associated with the modeling process.

Keywords: Watershed Modeling, HBV-EC, northeastern British Columbia, Blueberry River, Hydrology, Oil and Gas, Water Resource Management.

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Chapter 1- Introduction

1.1 Purpose of Study

The demand for fresh water supply has increased due to growth in population, industry and agriculture in many parts of the world. There is growing recognition that fresh water demand will exceed supply in more areas in the near future (Addams et al., 2009). With continued emissions of greenhouse gases, changes in regional temperature and precipitation patterns are predicted to influence regional hydrology, likely impacting water-related resources and water-dependent activities (Schnorbus et al., 2012). As a result, water may become the World's most sought after natural resource. Theoretically, there is sufficient fresh water to sustain the current population if evenly distributed (Islam et al., 2007). However, water distribution is far from even, and some regions already experience scarcity, which can affect urban, agricultural, and industrial development. In many parts of the world, governments are given the task of assessing the water supply and allocating it for the good of the society, while maintaining sufficient discharge for natural ecological function.

Fresh water is used in hydrocarbon extraction and, like water, hydrocarbons are irregularly distributed and are commonly distant from a fresh water source. Thirty-eight percent of shale gas reserves across the world are in areas that are considered under high water-stress, i.e., there isn't enough water locally to sustain development (Reig et al., 2014). Water shortage is a significant business risks for companies exploring in at-risk regions. The risk of shortages and the multiple, potentially competing, demands on available water emphasize the vitality of water management and forecasting tools. The significance of this project lies in the growing importance and concerns about global water shortages and the impact of climate change on an already threatened resource, in light of the essential role that water plays in industry. Presently, Canada is considered to have "Low to Medium" water stress in shale gas areas (Reig et al., 2014), but as climate changes it is prudent to begin preparation for the possibility of enhanced water stress.

In this thesis I test the usage of the Hydrologiska Byråns Vattenbalansavdelning-Environment Canada hydrology modeling software (here forth referred to as HBV-EC) to assess future climate risks to the oil and gas industry, the agricultural industry and to the river itself in regards to water use and withdrawal from the upper portion of the Blueberry River Basin in Northeastern British Columbia. In order to assess said risk, hydrological simulations were run using the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) A1B emission scenario, under the CGCM3.1/T47 Global Climate Model (GCM). The selection process for this model is described in section 3.5.

1.2 Previous Work

The British Columbia Oil and Gas Commission (OGC) has a mandate on behalf of the people of British Columbia to ensure that the industrial demand for water associated with the oil and gas industry does not exceed the supply within its area of jurisdiction. Water usage is controlled through a process of granting annual water extraction "approvals" in the form of short or long-term licences, permitting approvals fall within the guidelines of the Environmental Flow Needs (EFN), as implemented by the OGC. This approval process is supported by the NorthEast Water Tool (NEWT), a GIS-based hydrology decision-making tool, developed by the OGC in August 2012, which serves to assess the historical and currently available flow rates against the requested withdrawals for a particular project. The OGC developed NEWT in collaboration with staff from the BC Ministry of Forests, Lands and Natural Resource Operations (FLNRO) to evaluate monthly and annual discharges from various stream networks in Northern British Columbia (Chapman et al., 2012). Through the Oil and Gas Activities Act (OGAA) the OGC uses NEWT amongst other tools as part of their evaluation and authorization of Section 8 Water Use Approvals, which are required by industry in order to draw water from streams or lakes for various oil and gas activities (Chapman and Boyd, 2014). To-date, NEWT has not been used to forecast future withdrawal limits and/or to model changes in flow rates that could jeopardize present withdrawal in northeastern British Columbia.

A recent study focused on the long-term suitability of the Athabasca River (Alberta, Canada) as the water source for oil sands mining (Sauchyn et al., 2015), draws upon streamflow and paleohydrology records to argue for caution in the assumptions that water supply in the Athabasca will always match the needs of this long term industrial investment. While allocations for fresh water withdrawal in the Athabasca River may be supported by current seasonal fluctuations in flow, they may not be supported when considering long-term climatic variability. This was demonstrated using a 900-year tree ring reconstruction of the water-year flow, accompanied with decadal scale data on stream discharge variability, which identified a long-term decline in flows through the

Athabasca River Basin as well as periods of significant and prolonged droughts (Sauchyn et al., 2015). The results of this study raise questions concerning the underlying assumptions about the representativeness of the short-term instrumental record, and lend support for the development of alternative forms of analysis for an area such as the Montney Basin, an unconventional natural gas play in northeast BC, situated around the Peace River.

An earlier study in 2010 monitored the impact of climate change and harvest of mountain pine beetle stands on streamflow in northern British Columbia (Hirshfield, 2010). This study used HBV-EC as a hydrological modeling tool, in conjunction with numerous emission scenarios and GCMs, to model the streamflow of Moffat Creek and Goathorn Creek (British Columbia, Canada). Under the same A1B emission scenario that will be used in this study, all the GCMs tested in Hirshfield's study observed streamflow peaking earlier in the year, between the years 2010-2100 (Hirshfield, 2010). There was also a strong agreement between GCMs tested that spring freshet flows (peaks) will occur one month earlier than they did during the calibration period. Peak discharges were simulated to be forty percent greater than baseline over all time periods (Hirshfield, 2010).

1.3 Objectives-

In this thesis, I use a quantitative watershed model to predict discharge in the Blueberry River Basin between the years 2046-2065, given GCM predicted changes in climate. In order to predict the influence these changes have on industry, current withdrawal approvals from NEWT are compared with forecasted monthly discharge to predict future water availability.

Each of the major components of this hypothesis can be viewed as steps that, once the first is confirmed, the next can be tested. The first step, correlating historic discharge with past climate data, is the formative problem that must be addressed. To do so parameters must be set in the software to define the watershed, and if correlation is confirmed through statistical testing, these parameters may then be used to forecast future streamflow. Without a statistical agreement between observed and correlated discharge from known climate conditions, the model may not be used for future conditions. Assuming this is accomplished, the meteorological data that is required by the modeling software must then be obtained for a future climate scenario, in order to simulate discharge. If this occurs, data may be entered into the software, and simulated discharge can be compared to current withdrawal allocations, in order to assess the sustainability of current allocations under these simulated conditions.

Chapter 2. Study Area

2.1 Climate and Vegetation

The province of British Columbia has a diverse climate and distribution of vegetation spanning Mediterranean-type, semi-arid, subarctic to alpine environments. Topography ranges from plateaus, plains, basins and both central and coastal mountain ranges. While the majority of the province is heavily forested, there are also regions of grasslands, wetlands, scrub and tundra (Pojar and Meindinger, 1991). Valentine et al.

(1978) designate five physiographic zones (Fig. 1) within the province of British Columbia. In addition to physiographic zones, the province is divided into fourteen biogeoclimatic zones (Fig. 2) to describe the unique climate and vegetation of the region. My area of study is the Northern district of the province, between the Northern and Central Plateaus and Mountains, and the Great Plains.

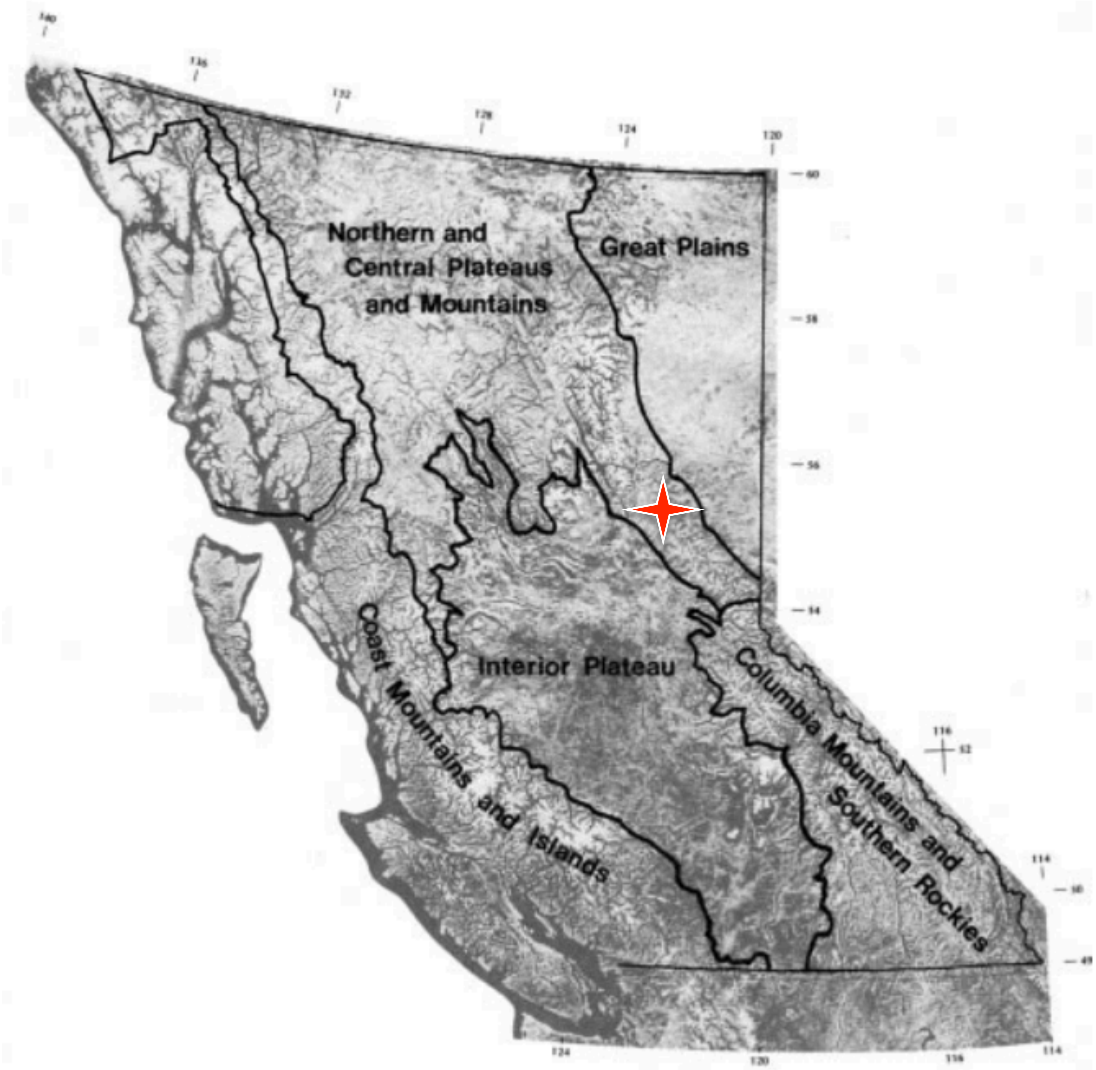

Figure 1 Generalized Physiographic Zones of British Columbia (Adapted from Pojar and Meindinger, 1991). Red star indicates approximate location of Blueberry River.

The mountainous region runs from just north of Central BC (approximately 56º North) to the Yukon/Northwest Territories border, westward to the Coastal Mountains and Islands, and eastward to the Great Plains. The Great Plains begin at approximately the same latitude and are bordered by the Northwest Territories and Alberta. Streams commonly cross the plateaus in the region, which were once covered by Pleistocene ice. Mountains in the region are slightly more subdued than those of Southeastern, and Coastal British Columbia. The Great Plains lie eastward of the Northern Mountains, and are characterized by their flat to gently sloping sandstone and shale beds. The topography in the area is gentle and rolling, with the exception of the regions cut by the Liard River, Peace River, and their associated tributaries. Outwash gravels, sands and lacustrine clays and silts are very extensive within this zone (Pojar and Meindinger, 1991).

The primary determinants of climate in British Columbia are the Pacific Ocean and the Rocky Mountains (Holmes et al., 2015). The Pacific harbors heat and moisture that is delivered eastward where it encounters the mountains. As air is driven upwards, it drops the majority of its precipitation, forming very wet conditions west of the Rockies, and due to the subsequent rain shadow that forms, desert like conditions east of the range. The majority of precipitation is dropped in early summer, and in most regions, winter precipitation comes in the form of snow. Not only do the mountains influence precipitation, they also act as a barrier to westward moving Arctic air, resulting in moderately temperate winter conditions for the majority of the province, save the Great Plains. It is because of this phenomenon that winter temperatures commonly reach -40ºC in northeastern British Columbia. The harsh winters in the study area greatly influence the vegetation that grows in the region. The region surrounding the Blueberry River is predominately Boreal White and Black Spruce, with some inclusions of Willow, Birch, Alpine Tundra and Subalpine Fir (Pojar and Meindinger, 1991). Muskeg is also abundant in the region, which can cause difficulties in both transportation and infrastructure for oil and gas activity.

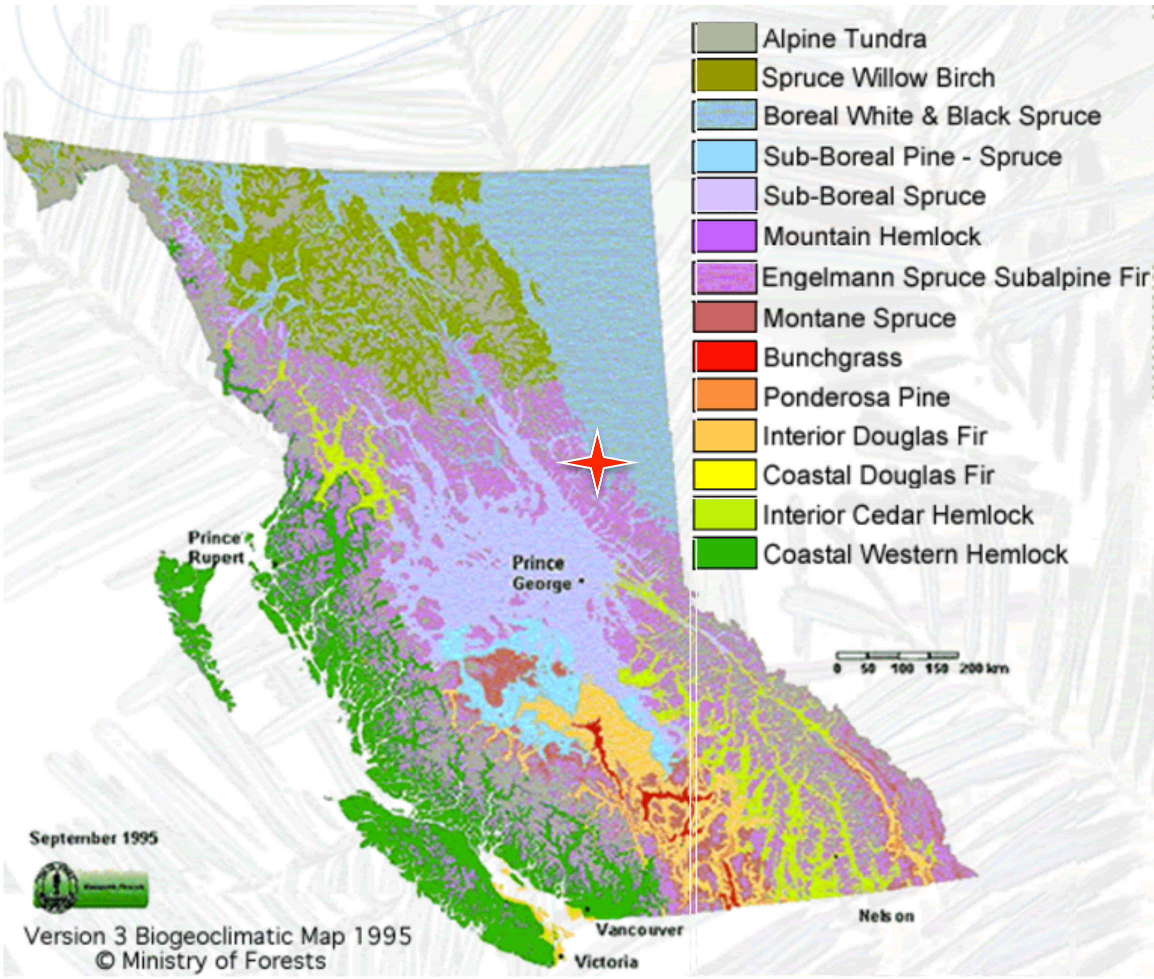

Figure 2 Biogeoclimatic Map of British Columbia (Adapted from Ministry of Forests, 1995). Red star indicates approximate location of Blueberry River.

2.2 Brief History of Oil and Gas Development-

The oil and gas industry has played a significant role in British Columbia for over a century. Records of natural gas powered street lights can be traced back to 1904 in some locations, while the Royal Canadian Oil Company reportedly drilled the first successful oil well in 1907, producing approximately 20 barrels a day (Wemyss, 1992). This early well was much different than what one would see today, in terms of technology and methods used and the volume of production. The first commercial natural gas well drilled produced approximately 339,600 m^3 of natural gas per day near Peace River, in 1922 (Wemyss, 1992). Realizing the newfound economic potential of the area, the British Columbia government shortly after froze all activity for 25 years, claiming all development should come from the government.

In 1942 land was reopened to private companies in British Columbia to drill for oil and gas. Simultaneously, in 1942 the United States government completed the Alaska Highway, permitting access to regions previously deemed inaccessible. Given this accessibility, the coming decade saw rapid oil and gas exploration in British Columbia. In 1947, Imperial Oil made a significant discovery in Leduc AB, which led to further discoveries in Devonian limestone and dolomite reefs stretching towards British Columbia (Wemyss, 1992). Within ten years, five additional gas fields were discovered, and the TransMountain and Westcoast natural gas pipelines were built. Shortly after in 1959, British Columbia built two refineries in Taylor and Prince George, and major discoveries continued north of Fort St. John (Wemyss, 1992). The largest discoveries were made in Triassic oil fields in Fort St. John, gas-rich Cretaceous deposits south of Dawson Creek, Devonian reefs in Fort Nelson, and in Mississippian aged faults from the foothills near Chetwynd. These regions had a net yield of approximately half a billion barrels of oil and 566 billion m^3 of natural gas (Wemyss, 1992).

Prior to 2005, production of natural gas in the Montney Basin, a Triassic aged hydrocarbon rich basin, was restricted to conventional drilling, in poor quality fine-grained sandstone reservoirs. In 2005, the first attempt at horizontal drilling was made in the Montney Formation, near Dawson Creek. Production from this well was 4-5 times greater than previous vertical wells in the formation. This spurred development and research in the area, which lead to the 26,000 km^2 unconventional Montney play being discovered (Hayes, 2012).

Due to efficiency and reduced cost of horizontal drilling techniques, unconventional gas has taken the forefront of exploration and development in Northern British Columbia. Unconventional resource development began in the mid 1990's in the Jean Marie Devonian carbonates, followed by the Early Cretaceous Cadomin Formation, and in 2005, the Cretaceous sandstones (Hayes, 2012). As previously mentioned, shale gas developments in the Devonian Muskwa, Otter Park and Evie shales in the Horn River Basin, and Triassic aged siltstones of the Montney have all been produced, with immense success. The Montney has been the most productive basin, as indicated by Figure 3, which plots monthly gas production in e^3m^3 (thousands of cubic meters), from 2005 onwards (Hayes, 2012). Figure 4 demonstrates the relationship between conventional and unconventional production in northeast British Columbia, with unconventional gas production overtaking conventional production in 2011 (Hayes, 2012).

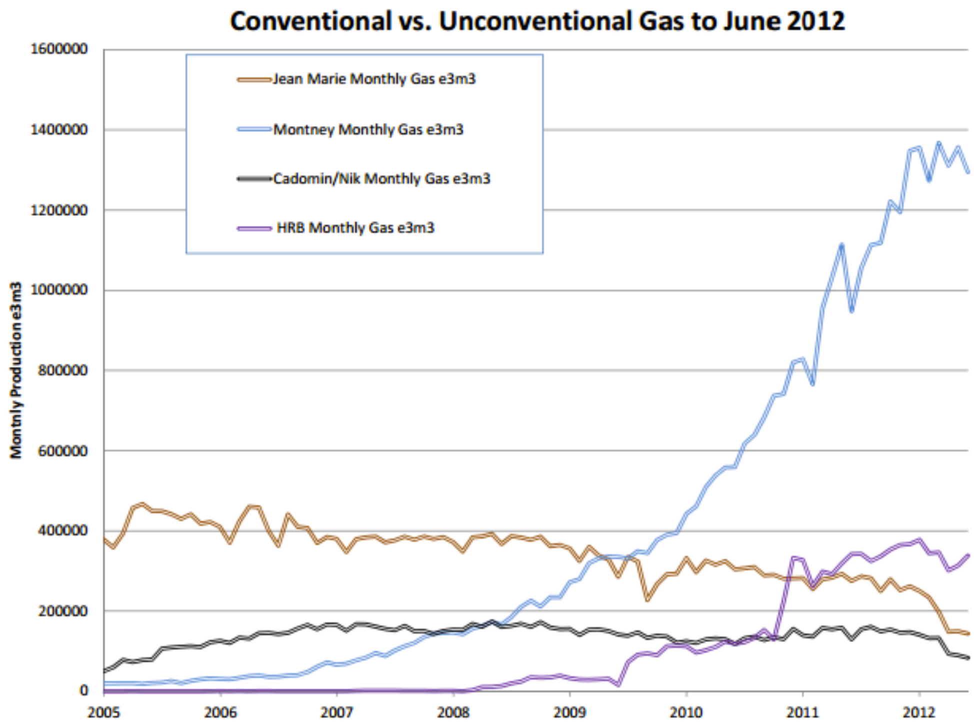

Figure 3 Trends of Jean Marie, Montney, Cadomin and Horn River Basin gas plays from 2005-2012 (Hayes, 2012).

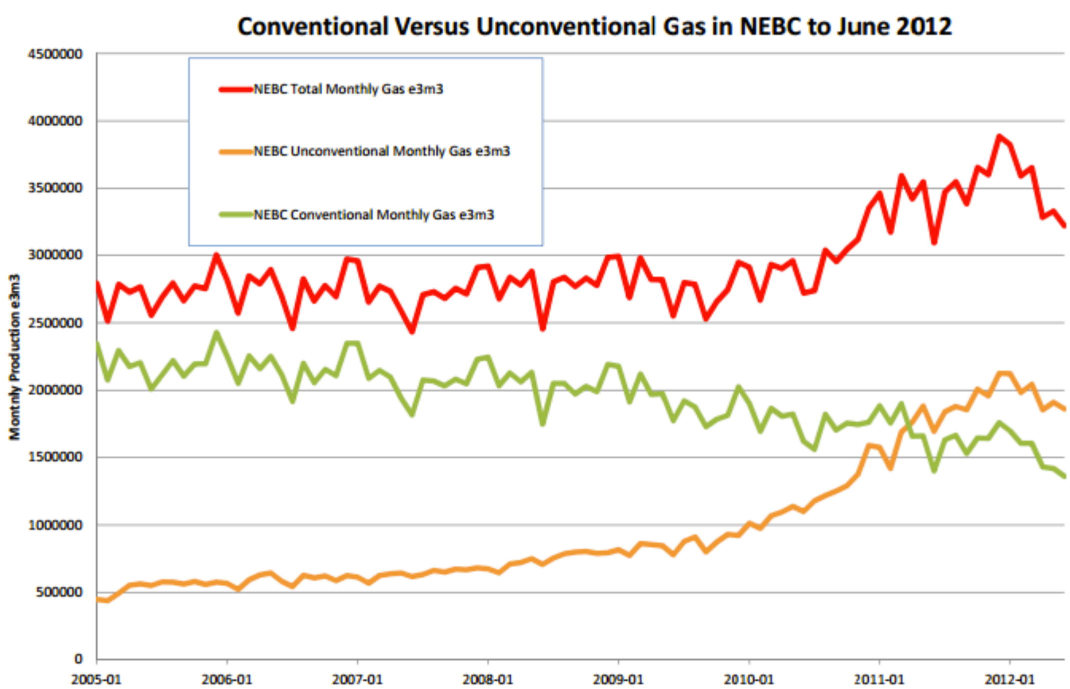

Figure 4 Trends of conventional and unconventional production from 2005-2012 (Hayes, 2012).

According to Table 18 of the *2014 Annual Report on Water Use for Oil and Gas Activity* published by the OGC (Boyd, 2014), there were 594 natural gas wells in the Montney Basin that used water for hydraulic fracturing (Montney North, and Montney Heritage areas). The mean total volume of water required to produce wells in the Montney Heritage formation is 10,383 m^3/well and 11,953 m^3/well in the Montney North. Although these are not the greatest per-well water requirements for hydraulic fracturing (the Liard Basin requires 88,634 m^3/well), due to the sheer number of wells in the basin, in 2014 the Montney North and Heritage accounted for 80.7 percent of the total water use for hydraulic fracturing in northeast British Columbia (Boyd, 2014). Unconventional shale gas development in northern BC targets dry natural gas from the Middle Devonian over pressured shales of the Muskwa, Otter Park and Evie Formations. Shale gas in the Montney Play was conventionally developed from Triassic sandstones, however, with the advent of horizontal drilling and hydraulic fracturing, natural gas can be extracted from the much tighter siltstones. Prior to 2005, the Triassic sandstones had produced 25 billion cubic feet (BCf) of gas. As of June 2012, production from the Montney approached 1.3 trillion cubic feet (TCf), largely thanks to unconventional drilling techniques. As of October 2012, 1,100 active gas wells were present in the Montney, nearly all of which were drilled using horizontal techniques. Daily production in 2012 was 1.5 BCf/day, with expectations to double or triple this rate of production by 2020 (Hayes, 2012).

2.3 The Blueberry River Basin-

Northeastern British Columbia covers an area of approximately 175 500 km^2 (NEWT, 2015). The region has a north/south extent from south of Dawson Creek to the Yukon-Northwest Territories border, and an east-west extent from the Alberta border to the Rocky Mountains. Within the regions defined as northeastern British Columbia, there are four major unconventional gas plays, the Cordova Embayment, Horn River Basin, Liard Basin and Montney Basin (Fig. 5) (Chapman et al., 2012). The focus of my study is within the Montney Basin, in the Blueberry River watershed. The Blueberry is a tributary to the Beatton, Peace and eventually, McKenzie River drainage system. The Blueberry Basin is centered at 56°49'44" N, 121°36'01" W. The Blueberry River Basin contains two major tributaries, as Aitken Creek joins the Blueberry River, continuing on as the Blueberry downstream. Both rivers previous to this junction are alike in size, discharge, and have similar allocations for industry withdrawal. The sub-basin measures approximately 1 777 km^2, and has a mean elevation of 825 m. The elevation where stream gauge measurements are taken is 650 m. The Blueberry River watershed upstream of Aitken Creek produces a mean annual runoff of 172 141 921 m^3, while the total mean annual runoff of the entire Blueberry basin is 293 278 540 m^3 (NEWT, 2015). The mean discharge in the Blueberry River is 5.45 m^3/s (1981-2010), however winter flow in limited between the months of December to March (NEWT, 2015).

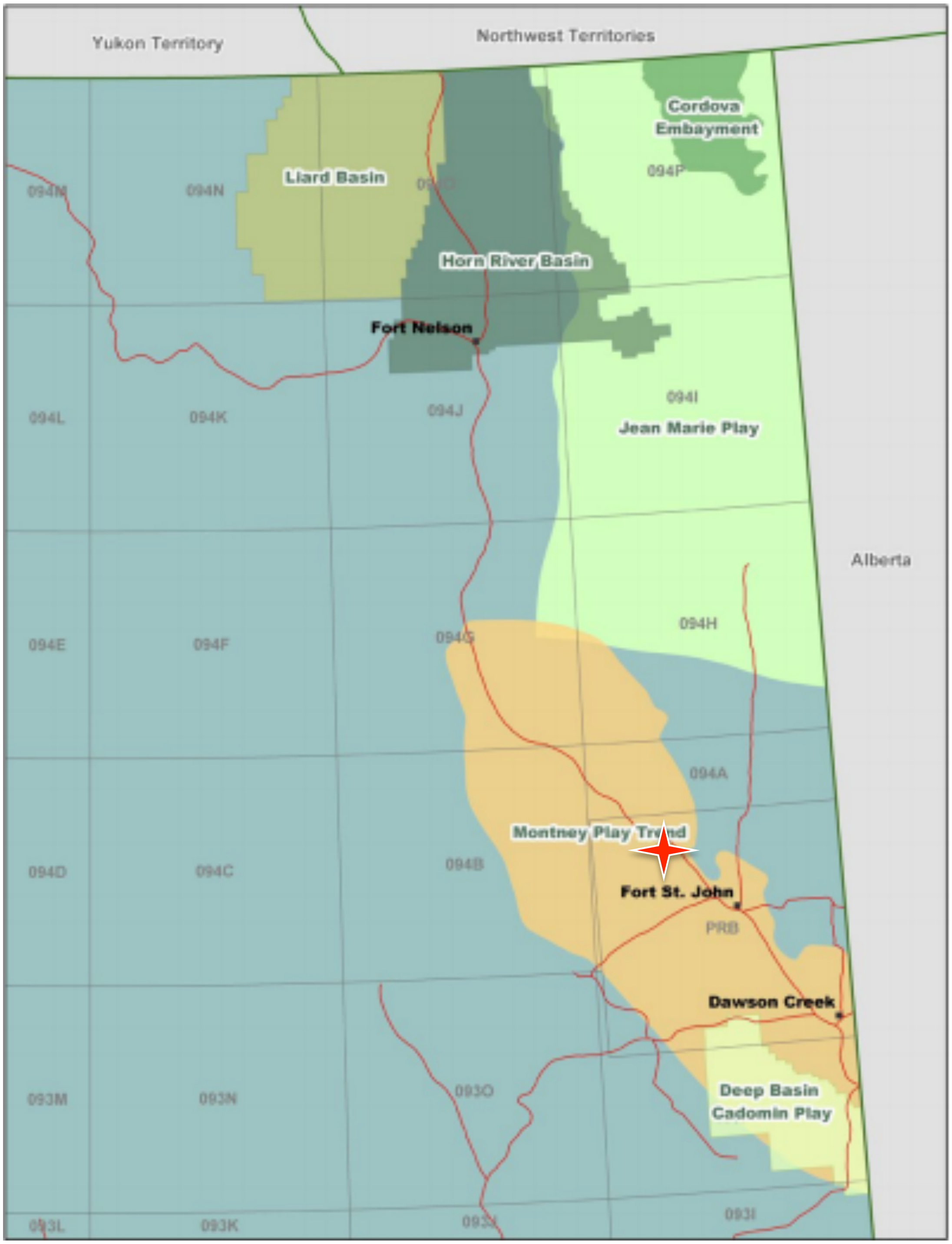

Figure 5 Northeastern British Columbia basins encompassed by NEWT, red star denotes approximate location of Blueberry Basin (NEWT, 2015).

Chapter 3. Methods

3.1 Selecting a Watershed Model-

There are numerous hydrologic models that vary in functionality and complexity, available as tools for forest management and climate change analysis (Beckers et al., 2009). Modeling Canadian watersheds is historically difficult due to data limitations and the complicated nature of cold region hydrology (Pomeroy et al., 2007), where air temperature remains below zero for more than half of the year. Under these conditions, snow, frost and ice are common (Woo et al., 2007), resulting in significant snow cover and snowpack water storage (Pomeroy et al., 2007). British Columbia watersheds are also commonly subject to the high elevations of the Rocky Mountains, which plays a significant role in watershed water budgets (Tong et al., 2008).

Beckers et al. (2009) ranks and evaluates numerous watershed models according to characteristics including data requirements and complexity, for forest management and climate change applications in British Columbia and Alberta. For modeling the Blueberry, I considered several models based on the extent to which my data could be used to satisfy the objective of the study, the accessibility of the software, and the reviews from Beckers et al. (2009). After an initial review, two models were selected for further consideration, WATFLOOD and HBV-EC, both of which are offered in the Green Kenue processing tool.

3.1.1 Green Kenue-

Green Kenue is a pre- and post-processing tool for WATFLOOD, Raven, UBC Watershed and HBV-EC hydrologic models. Green Kenue serves as a modeling environment for watershed flows, runoff, flooding and other hydrological surface events (Green Kenue, 2010). Green Kenue is under copyright to the Canadian Hydraulics Centre, National Research Council, was funded in part by Environment Canada, and distributed free of charge by the National Research Council of Canada.

3.1.2 WATFLOOD-

WATFLOOD, one of the hydrologic models offered by Green Kenue, was developed by the University of Waterloo, and is primarily applied to study flood forecasting, and long-term hydrologic simulation from precipitation data. This precipitation data may be acquired from weather models or radar (Kouwen, 2008). WATFLOOD models input variables such as interception, snow accumulation, ablation and infiltration, as well as output variables such as evaporation, interflow, recharge, baseflow and overland/ channel routing (Kouwen, 2008). This model ranks as a mixed model for simulating Soil Vegetation Atmosphere Transfer (SVAT) processes. Evapotranspiration, snowmelt and infiltration are calculated within the software, therefore WATFLOOD requires at minimum, temperature and precipitation data as meteorological inputs (Beckers et al., 2009). WATFLOOD ranks as a high complexity model, with low-medium functionality for forest management (Beckers et al., 2009) and is hence suitable to be used by a modeling team with several months to half a year to run the model. Furthermore, the model is limited by its simplified snowmelt calculations, and is best applied in gradual terrain in either strictly snow or rain conditions, but not mixed setting (Beckers et al., 2009).

3.1.3 HBV-EC-

The HBV-EC (Hydrologiska Byråns Vattenbalansavdelning- Environment Canada) model is a conceptual watershed model initially developed by the Swedish Meteorological and Hydrological Institute (SMHI) (Beckers et al., 2009). Environment Canada adapted this model in collaboration with the University of British Columbia (UBC) in order to recreate watershed responses in terrains more suited to the Pacific Northwest and other environments alike. HBV-EC uses a unique climate zone algorithm, to enhance the representation of lateral climate gradients across the basin (Green Kenue, 2010). Within each zone, climate parameters such as temperature and precipitation lapse rates are uniquely distributed. Runoff from these zones is grouped as fast and slow response reservoirs, similar to the original HBV model. The HBV-EC model also responds to changes in slope and aspect, when accounting for snowmelt (Green Kenue, 2010). This is an important parameter to adjust in mountainous terranes, where significant elevation and aspect changes are observed.

Like WATFLOOD, HBV-EC requires monthly average temperature and evaporation-rate values, in addition to daily temperature, rainfall and snowfall measurements (Beckers et al., 2009). The HBV-EC model is limited by its single treatment of canopy snow storage (Moore et al. 2007), and simplified channel-routing routine (Beckers et al. 2009). Previous work has been applied in small to medium watersheds in mountainous setting, with discharge being primarily driven by snowmelt (Beckers et al., 2009). Much like WATFLOOD, the temperature-index snowmelt method is better suited for strictly snow or rain regimes, not mixed. The HBV-EC model is ranked as being of Medium Complexity, with intermediate functionality for forest management (Beckers et al., 2009).

3.2 Historic Climate and Discharge-

Natural Resources Canada (NRC) climate data provides an array of daily, monthly, and annual climatic data. The nearest climate station to my study area was the Wonowon station (56º44' N, 121º48' W), which has complete historical data from 1973-1991. This data includes but is not limited to temperature, precipitation, and snowfall. Additional snow data was taken from the Fort St. John Airport snow station (56°14'17" N 120°44'25" W), (FLNRO, 2016) which measures daily snow pack depth and snow liquid volume. Mean monthly temperature and evapotranspiration was taken from Climate WNA, a PRISM-based tool that extracts and downscales monthly climate, and solar radiation data from 1961-1990, and calculates monthly, seasonal and annual climate variables for numerous locations based on spatial coordinates and elevation (Wang et al., 2012).

Historic hydrologic discharge data was collected from Station 07FC003- *Blueberry River below Aitken Creek*, operated by Environment Canada and the BC Ministry of

Environment (56°40’ N, 121°13’ W). Discharge data in m^3/s is available from 1965 onwards, with recordings of daily and monthly averages, as well as annual extremes (daily average) and annual peak flows.

3.3 Green Kenue-Building the Watershed-

3.3.1 Choosing a DEM-

The accuracy of modeling hydrological and environmental processes is contingent on topographic data that recreates the true structure and processes of the watershed (Abdollah et al., 2015). Digital Elevation Models (DEMs) are the base topographic data that are input into a hydrologic model, and range in cost, spatial coverage, accuracy and grid size (Robinson et al., 2014). A DEM that doesn’t replicate the true form of the basin may manually be edited to improve DEM performance. There is an array of processes that serve to improve DEM accuracy, each with limitations and benefits. These editing techniques use known stream networks to trench or mathematically warp the original DEM to enhance the accuracy of stream characteristics, and to better replicate known conditions (Callow et al., 2007).

Green Kenue offers an array of techniques to improve the accuracy of the DEM, citing that the delineation of channels and watershed boundaries are contingent on the accuracy of the DEM. Cross referencing the locations of channels and boundaries with GIS data is encouraged before editing, and can be displayed in view alongside DEM generated channels in the program (Green Kenue, 2010).

The DEM files I used for my study were imported from Geogratis (NRC, 2016). The DEM files provided are 1:50,000 scale, covering an area of approximately 19 200 hectares, which is equivalent to an individual Map Sheet Unit in an NTS coordinate system. The Map Sheet Unit is then divided into east and west portions, each covering 9 600 hectares. The Blueberry Basin covers an area of approximately 177 674 hectares, therefore 16 DEM files were needed to cover the region.

Individual DEM files were stitched together by creating a regular grid in Green Kenue and uploading DEMs using the MapObject Tool. This process imported topography from each DEM to the new regular grid. This grid could then be saved as a 2D Rectangular Scalar Grid file (.r2s), and used as a DEM to build the watershed. Once the DEM was imported into the new Watershed, an outlet node could be assigned to the stream network.

3.3.2 Green Kenue- Defining Routing/Climate Parameters-

3.3.2.1 Assigning an Outlet Node-

The outlet node that Green Kenue assigned during basin generation was further downstream than I intended to measure, so a node closer to the 07FC003 stream monitoring station was selected. The newly assigned outlet node is located at 56º40’21”N, 121º13’30”W elevation 658m, while the NRC Water Office measurement station is located at 56º40’39” N, 121º13’20” W elevation 650 m (Figure 6). Once an outlet node was assigned, a flow algorithm was selected to generate the basin channel network.

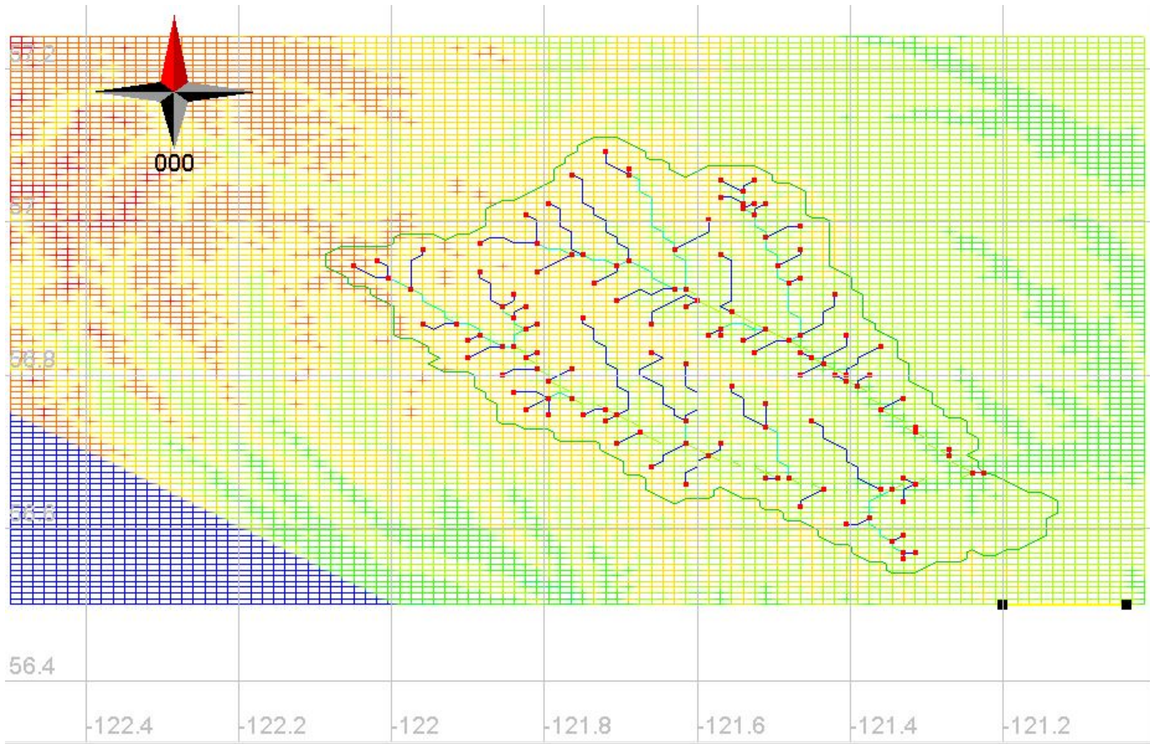

Figure 6. Delineated Stream Network in the Blueberry River Watershed, Green Kenue. Green outline indicates watershed boundaries. Black dots in lower right corner are 10 km apart. Outlet node is the right-most red dot.

3.3.2.2 Generating Channel Networks-

To generate the basin channel network I used the A^t algorithm, a tree search algorithm that doesn't modify the DEM, permitting a more genuine reconstruction of channel delineation (Green Kenue, 2010). The A^t algorithm computes the flow areas, identifies drainage channels, and generates a default basin from the basin outlet. The channel paths are defined by connecting nodes of the DEM that coincide with the path of surface water flow. Channels, or flow paths, are assigned a stream order and a corresponding drainage area. Stream order is the measurement of the relative size of the channel. First order streams are the headwater channels, and as two channels of the same order meet, the newly formed single downstream channel acquires an order one greater than that of the two upstream channels. The extent to which flow paths are displayed is contingent on the assigned value of the Channel headwater drainage area. Only channels that conduct flow from areas greater than the specified channel headwater drainage area will appear in the watershed, and the user may assign this parameter. By increasing the minimum drainage area, the number of flow paths displayed in the view will decrease, while decreasing this parameter effectively increases the number of flow paths displayed (Green Kenue, 2010). I assigned the channel headwater drainage areas to be 5 km^2, because it produced a channel network that best matched the interpretations of the stream network, as interpreted from LANDSAT images, and NEWT.

Green Kenue offers the user an opportunity to edit many features of the watershed, including the DEM and channels, in an effort to ensure the correct location of streams and drainage basins. Due to the relatively high resolution of my study DEM, and by comparing the created channel network to LANDSAT images, and the watershed in NEWT, I chose not to manually edit channels.

3.4 HBV-EC-

3.4.1 Physical Parameters-

HBV-EC assigns the watershed object basin properties such as channels, slopes, aspects, and climate/elevation zones. The number of climate zones is typically contingent on the size of the basin, with smaller watersheds normally being contained within one zone. Topographic features are defined into bands, including elevation and slope. The user manually defines land use, and the extent to which the model identifies aspect.

3.4.1.1 Area Calculations-

The HBV-EC model is one-dimensional, therefore the relative locations of varying terrains is not necessarily relevant. Instead, the model is simulated based on the total area of grouped characteristics (Green Kenue, 2010). For example, one grouped characteristic may be forested terrain in Climate Zone 1, within Elevation Band 3, and with a North Aspect. The number of areas is dependent on the number of physical characteristics the user assigns. My model consisted of one climate zone, five elevation bands, two types of terrain (forest and open), two slope bands and four aspect bands, the HBV-EC model will be executed for each of these 80 area combination possibilities. An example of the parameters that go into calculating an individual area is shown in Figure 7.

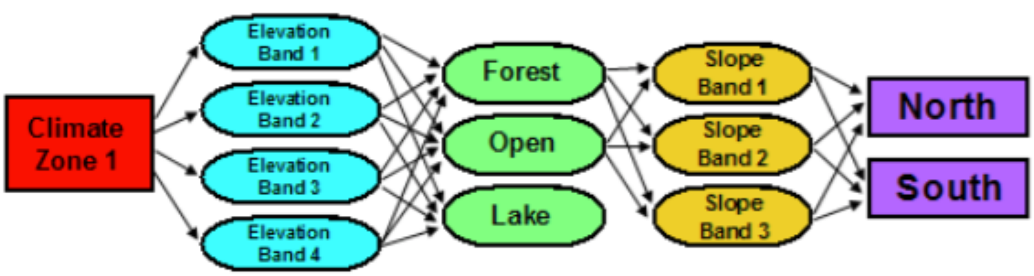

Figure 7 Example of how areas are calculated. In this figure there is 1 climate zone, 4 elevation bands, 3 terranes, 3 slope bands and 2 aspects, totaling 48 possible areas (Green Kenue, 2010).

3.4.1.2 Views-

Once the physical parameters of the watershed are set, the basin can be viewed in a 2- or 3-dimensional view. 2-dimensional views will be shown for each grouped characteristic in the following sections. Figure 8 demonstrates a 3-dimensional view of the Blueberry River Basin.

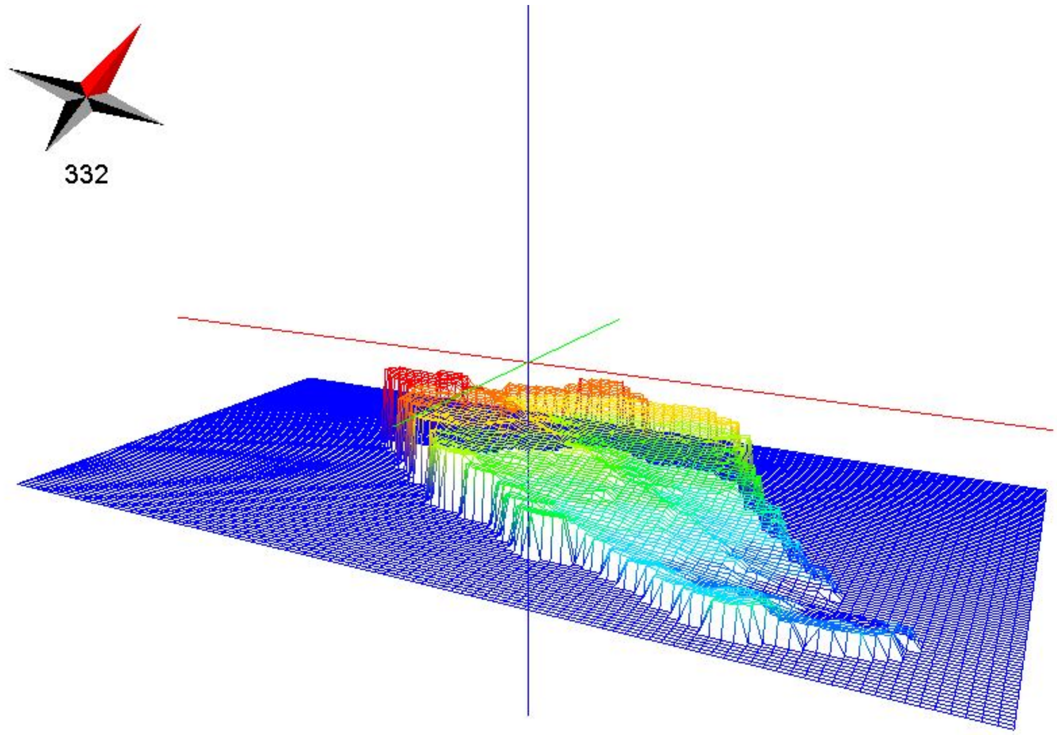

Figure 8. 3D view of the Blueberry River Watershed Model. Basin is ~1 777 km^2 (Green Kenue, 2010).

3.4.1.3 Climate Zone-

The Blueberry River watershed is relatively small, and relief is moderate, therefore only one climate zone was assigned. This assumes that there are not significant fluctuations in temperature, precipitation, snowfall, and other related parameters throughout the basin. Once a climate zone was defined, physical variables were assigned. These variables include Atmosphere, Forest, Snow, Soil and Glacier variables. Each of these variables has a subset of variables to be adjusted for the particular watershed. In calibrating this section, I referred to the parameters used in Hamilton et al., (2001), a study on Wolf Creek, near Whitehorse, Yukon. Wolf Creek was the northernmost study site I found that used the HBV-EC modeling software, and is within 4 degrees (N) of the Blueberry River Basin. The Whitehorse Climate Station is located at 60º42'34" N, 135º04’02” W at an elevation of 706.20 m, has a mean annual precipitation of 267 mm, 54 percent of which is snow, and a mean annual temperature of -3 ºC. The Wonowon Climate Station (56º44’ N, 121º48’ W) has an elevation of 914.4 m, mean annual precipitation of 543.5 mm, 35 percent of which is snow, and mean annual temperature of +1 ºC. Limitations encountered when assigning parameters in the Blueberry Basin included a lack of information on certain physical properties of the basin such as soil field capacity, canopy interception rates etc. Due to these limitations, and from the descriptions of the basin in the Wolf Creek study (Hamilton et al., 2001), an assumption was made that the Blueberry River exhibits similar physical responses to climate to the Wolf Creek Basin. Climate zone parameters used in the study are found in Table 3 in the Appendix.

3.4.1.4 Elevation-

The Elevation Tab (Fig. 9) included 5 bands ranging from 653 to 1028 m, each with equal elevation range, representing a maximum elevation change of 375m, while the average elevation of the basin was 825m.

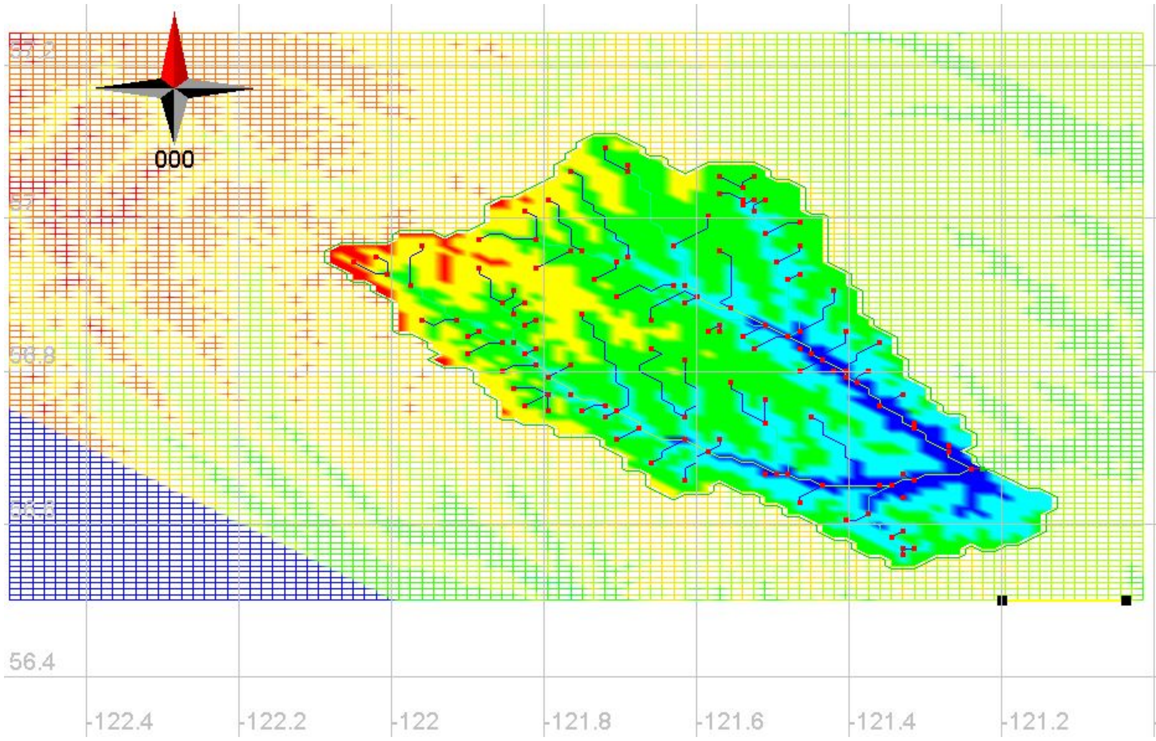

Figure 9 Elevation Bands of the Blueberry River Watershed, Green Kenue. Black dots in lower right are 10km apart. Red bands are the highest elevation, dark blue the lowest. Direction of flow is generally West to East.

3.4.1.5 Land Use-

Land use may influence the basin hydrology in terms of changes to peak flow, total runoff, and water quality and channel structure (Leopold, 1968). Changes in land use over time need be taken into account if model calibration takes into account past hydrologic behavior. Land use in the Blueberry River watershed has been primarily agricultural and forested with minimal development and logging in the last 35 years. Land use change over the last 35 years was manually evaluated through comparisons of LANDSAT images courtesy of the United States Geological Survey (USGS). LANDSAT images were evaluated for the years 1984, 1994 and 2015. Images for 1984 and 1994 were collected using Landsat 4-5, while 2015 was evaluated using Landsat 4.

Figures 10 and 11 depict the land use surrounding the Blueberry River Basin in the years 1984 and 1994. Based on the comparisons made between the LANDSAT images, I propose that no significant land use change has occurred since the historical data was collected, and parameters set in the calibrated period do not need to be adjusted for land use change when modeling.

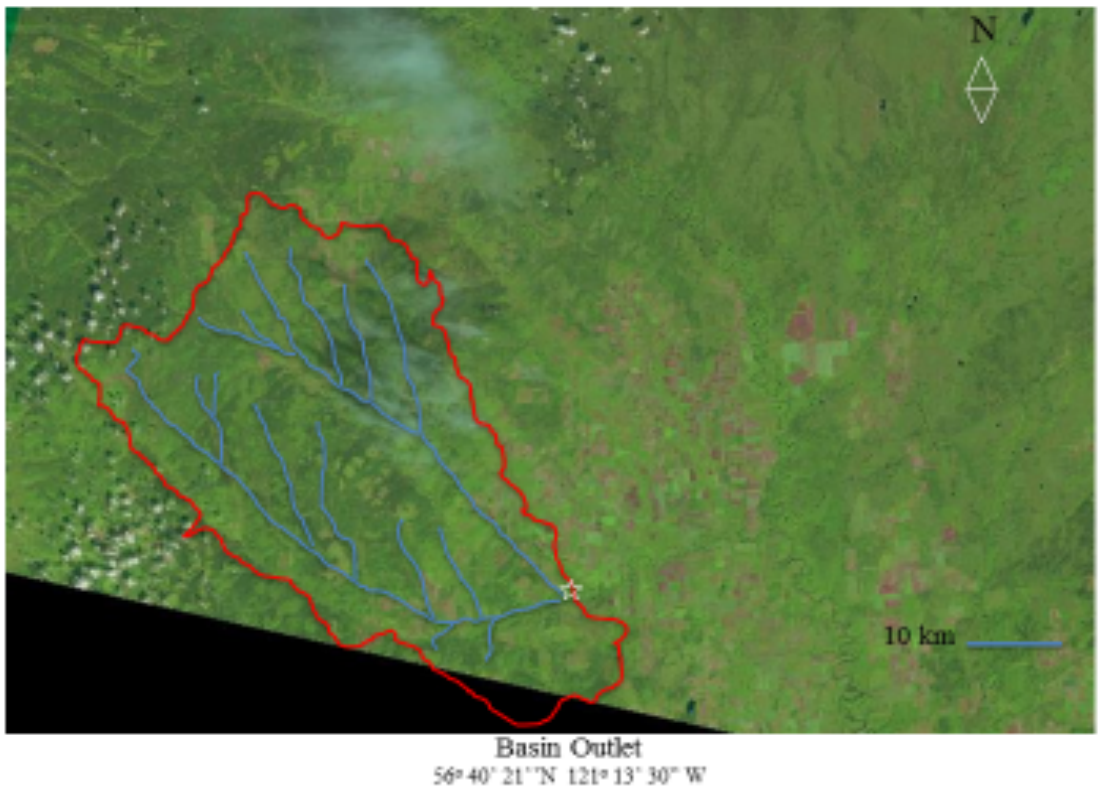

Figure 10 LANDSAT image of the Blueberry Basin in August 1984. Watershed designated in red, channels in blue (USGS, 2016).

Figure 11 LANDSAT image, of the Blueberry Basin in August 1994 (USGS, 2016).

LANDSAT images were used to evaluate and change in land use, however they were also used to identify regions of land use within the basin. There are four classes of land use that may be assigned in the Land Use tab in Green Kenue, Lake, Glacier, Forest and Open. The extent of the area each class covers influences how the watershed reacts to meteorological data. Zones may be identified using a GeoTIFF file that describes the climate or land use regions, or by using polygons. A GeoTIFF file was not available, therefore I used the polygons feature to define land use within the watershed (Fig. 12). Once a polygon was drawn, its land use could be assigned. My model consisted of two types of land use, Open and Forested terrain. In manually assigning land use there is a degree of error that was assumed to be insufficient to significantly alter calibration.

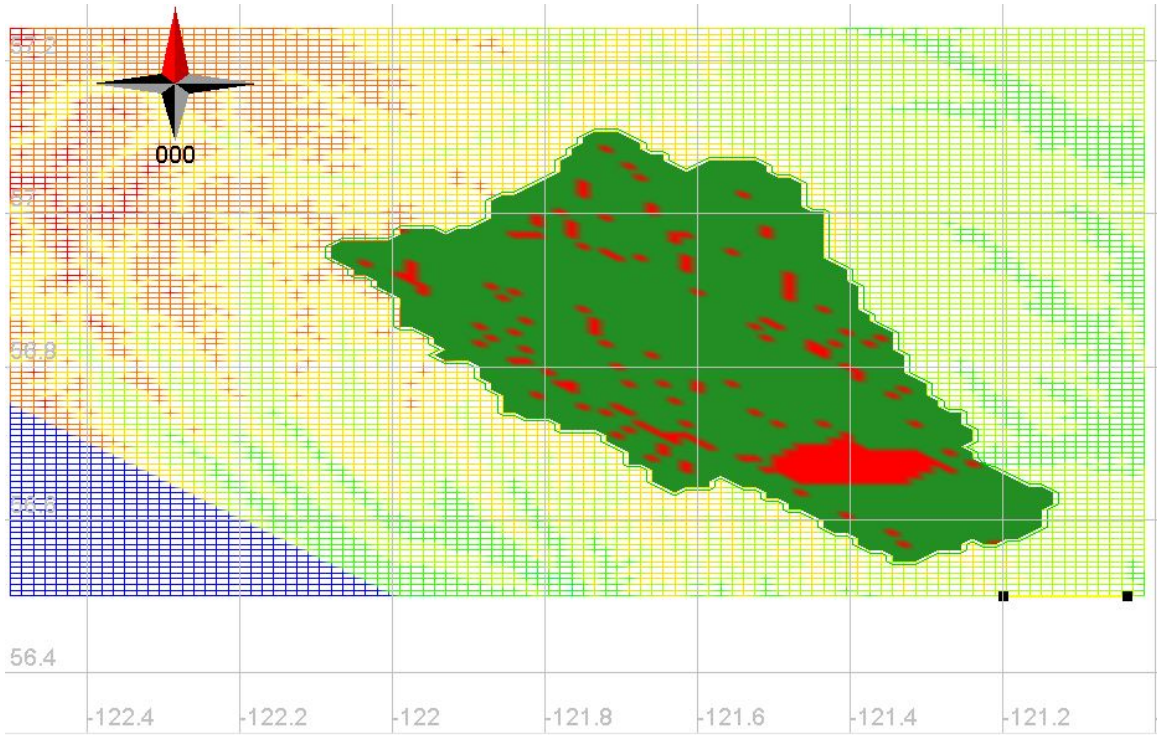

Figure 12 Land Use polygons in the Blueberry River Watershed, Green Kenue. Black dots in lower right corner are 10km apart. Red denotes open terrain, green forested.

3.4.1.6 Slope and Aspect-

The Aspect tab (Fig. 13) defines the direction the slope faces within the watershed. This value, in combination with the slope and elevation values defines the location and orientation of the land. The default aspect setting in Green Kenue is simply north-south orientation, where terrain is divided into either north-facing, or south-facing categories. Due to the vitality of snowmelt to generate stream discharge in spring months, this setting was changed to encompass all directions. By permitting more aspects to be recognized by HBV-EC, the software's ability to forecast snowmelt, and channel routing should be enhanced.

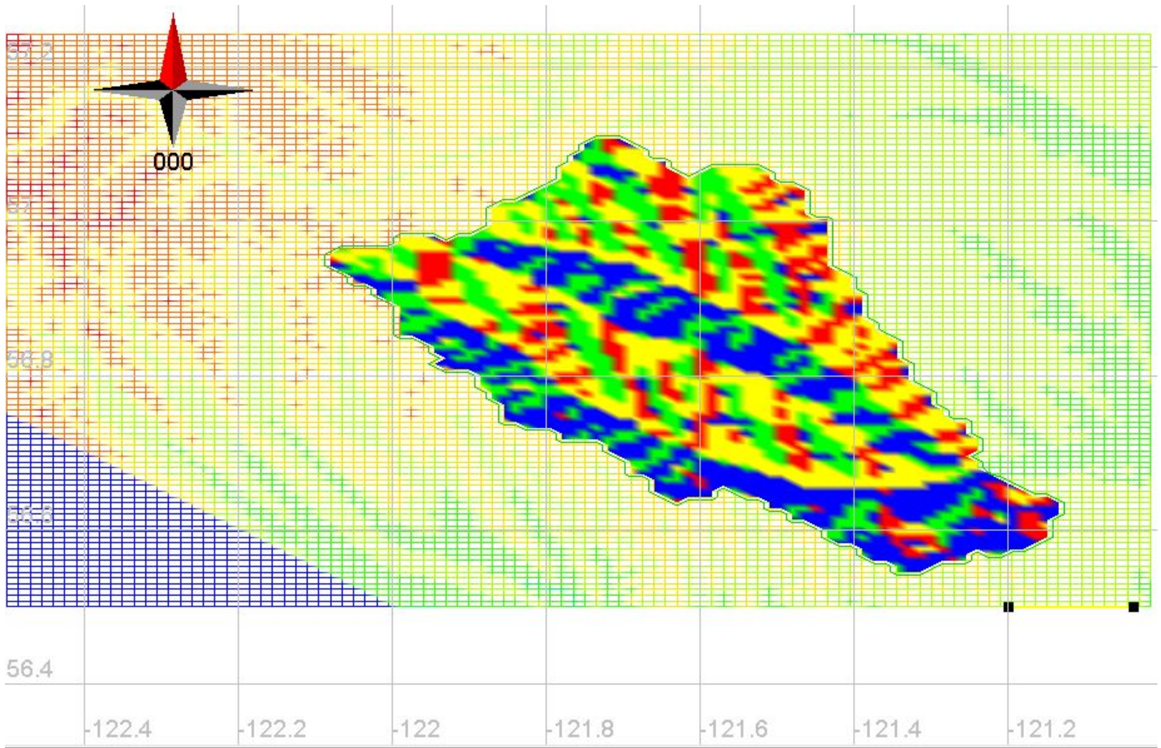

Figure 13 Aspects in the Blueberry River Watershed, Green Kenue. Black dots in lower right corner are 10km apart. Yellow is south facing, blue north facing, green west facing and red east facing.

The slope bands (Fig. 14) in the watershed follow the delineated channels and are divided into median slopes of 1.1 and 2.3. The higher slope band is depicted in red below, and ranges between 1.923 and 3.75, covering a total area of 333 km^2. The lower angled slope regions cover the majority of the watershed, with slopes in this band ranging from 0.02-1.92, covering a total area of 1 444 km^2.

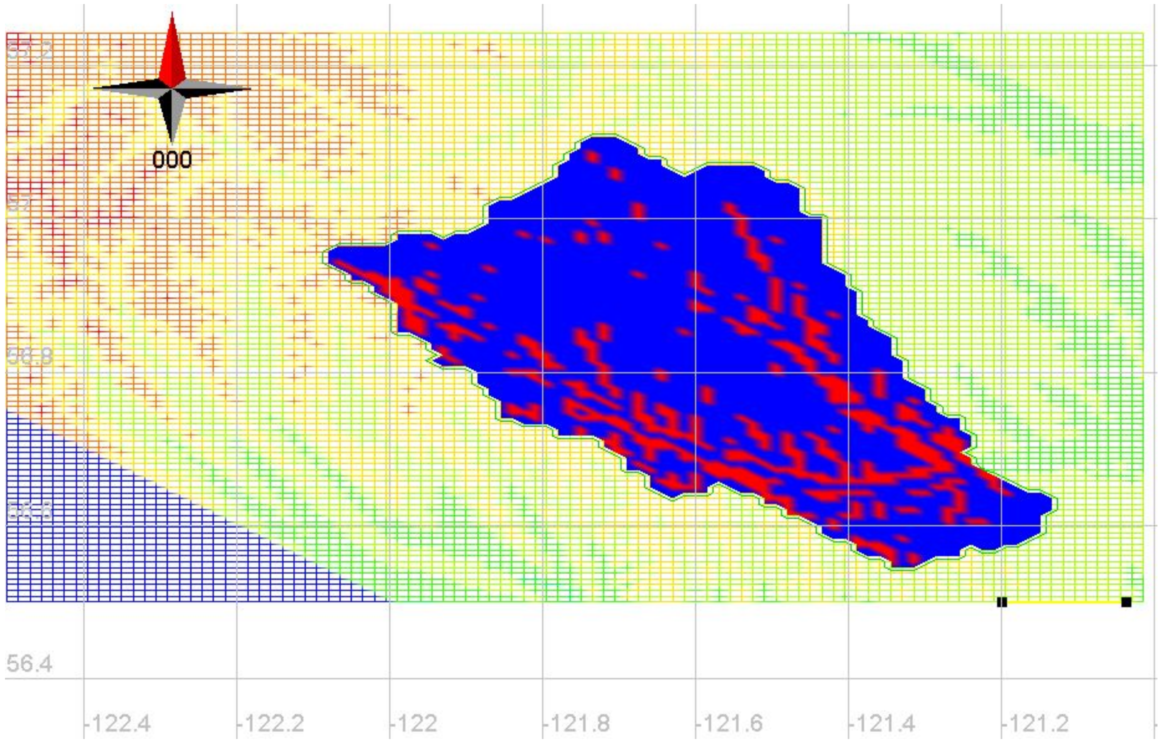

Figure 14 Slope Bands in the Blueberry River Watershed, Green Kenue. Red indicates high slopes, blue low slopes. Black dots in lower right corner are 10km apart.

Physical parameters assigned in HBV-EC determine how the model reads slope and aspect, and also provides an opportunity to input initial snow solid, liquid and moisture values. In doing so initial snow solid and liquid values are assigned to individual slope and aspect polygons within the basin. This process assumes that every aspect and slope would begin with the same initial snow solid and liquid values. Annual initial snow solid and liquid changed by year, depending on the climate of the previous year. Data for initial snow solid and liquid was taken from the nearest snow station, the Fort St. John Airport Snow Station (56°14'17" N, 120°44'25" W, elevation 694.9 m) (FLNRO, 2016). There is only one elevation-band parameter that may be adjusted, and this is the elevation of the band itself. This parameter may be changed if the majority of terrain is found in one region of the band, however the default setting is the band's median elevation.

3.4.2 Routing parameters-

Once the physical characteristics of the watershed have been defined, a model can be generated from the spatial basin data. The first step is to set a simulation start and end time, which must be done for each year the model is run. A 24-hour time step is used which runs daily temperature, precipitation and snowfall data, producing daily hydrometric data from the watershed response. Because of the way HBV-EC processes data on a daily time step, multi year periods with mean daily data do not simulate well, and better results are obtained from running data on individual years. When mean climate data is used as an input, outliers can skew the data, and the resultant discharge does not represented mean daily discharge. Before the model can be generated however, further basin parameters must be adjusted to create the most accurate watershed response to meteorological data.

The routing parameters to define when running a simulation in HBV-EC are implemented to the entire basin, irrespective of the number of land use classes or climate zones defined. These variables include the rate of percolation or fraction of runoff, proportion of fast and slow runoff release per day, and finally, the initial fast and slow reservoir discharge. Fast and Slow runoff release defines the portion of water that exits the stream through overland flow, as opposed to through percolation. A routing configuration must also be selected, either Parallel or Serial. Of the various studies reviewed, all used the parallel routing configuration. The final routing parameters are found in Table 3 in the Appendix.

Once the physical and routing parameters of the basin are set, the meteorological data is loaded into the model as an HBM file, which contains the name and location of the climate monitoring station, elevation, monthly mean temperature, evaporation, and daily temperature, precipitation and snowfall data for the year being modeled. The daily data I input into the .hbm files in order to calibrate the watershed was measured between 1978-1982 at the Wonowon Climate Station.

3.4.3 Model Output

The HBV-EC Model produces daily discharge in m^3/s. Data may also be extracted to be viewed in a 1-dimensional time series, displaying the following results: Total Discharge, Fast Reservoir Storage, Slow Reservoir Storage, Fast Reservoir Discharge, Slow Reservoir Discharge, Glacier Discharge, Glacier Ice Melt, and Glacier Water Storage. Two-dimensional time-varying triangular mesh data is also produced that represents the climatic conditions the watershed is exposed to, and can be viewed as an animation to see how the data progresses through time. Data that may be viewed in animation includes: Temperature, Rainfall, Snowfall, Soil Moisture, Soil Infiltration, Water Release, Evaporation, Snow Water Equivalent, Glacier Ice Melt, and Glacier Water Storage (Green Kenue, 2010).

3.4.4 HBV-EC Model Calibration

In order to calibrate this modeled discharge to known observed flow from the 07FC003 Station, both qualitative and quantitative measures were taken to assess the correlation. From a quantitative perspective, parameters were adjusted and the model re-run until timing and peaks of modeled and observed flow were aligned. While aligning these peaks and discharge events was done, the main focus was to replicate the shape of the hydrograph, in terms of timing of spring and fall events, when discharge was at a minimum. This focus was considered more important than matching peak flows due to the objective of the thesis - to evaluate water availability for industry use. Peak flow months are less susceptible to experience water shortages therefore are less likely to cause problems for industry withdrawal. Peak flow was rarely met in the calibrated model, however low flows were quite accurate. In order to assess the accuracy of the calibration, a number of tests were run on the quantitative agreement between the two. In Hirshfield's study of Goat Horn Creek, the following statistical tests were used to quantify calibration accuracy (Hirshfield, 2010) and these tests were also applied to my calibration.

3.4.4.1 Nash-Sutcliffe model efficiency coefficient (NSE)

NSE is a statistical test designed to quantify the accuracy of the model output (McCuen et al., 2006). NSE may be computed from daily or monthly discharge, and the resultant values determine whether correlation is satisfactory. The test quantifies the agreement between observed and modeled discharge. An efficiency coefficient of 1.0 is considered to be a perfect fit. Model calibration is considered satisfactory if NSE values for daily flow exceed 0.70, or monthly flow exceeds 0.8 (Singh, 2004). NSE is calculated using Equation 1.0-

$$NSE = 1 - \frac{\left(\sum_{i-1}^{n}(Q_{o}-Q_{m})^2\right)}{\left(\sum_{i-1}^{n}(Q_{o}-\bar{Q}_{o})^2\right)} \qquad (1.0)$$

where Q_o is observed discharge and Q_m is modeled discharge (Nash and Sutcliffe, 1970).

3.4.4.2 Coefficient of Determination (R^2)

The second statistical test run was the coefficient of determination. This test is essentially a square of the correlation coefficient (Krause et al., 2005). This quantitative statistic evaluates the proximity of dispersion of modeled values to the dispersion of observed values. Equal amounts of dispersion between modeled and observed values would produce a value of 1. R^2 is calculated by squaring the Correl Equation (1.1)-

$$R^2 = \left(\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}\right)^2 \qquad (1.1)$$

3.4.4.3 Root Mean Square Error (RMSE)

This statistical test (Equation 1.2) evaluates the error in discharge, expressed as m^3/s. In equation 1.2, n is the number of days of study, Q_o and Q_m values remain as listed above:

$$RMSE = \sqrt{\sum \frac{(Q_m - Q_o)^2}{n}} \qquad (1.2)$$

Values of zero indicate no error and hence a perfect fit. Singh (2004) suggests if values are calculated to be less than half the standard deviation, they are considered to be low.

3.4.4.4 Mean Volume Error (MVE)

The mean volume error (Equation 1.3) compares simulated and observed volumes. Ideal models will produce a MVE less than 0.1 however remain acceptable up to 0.15 (Hummel et al., 2003). MVE is calculated using the following equation:

$$MVE = \left| \frac{Q_o - Q_m}{Q_o} \right| \tag{1.3}$$

3.5 Future Climate

Predicting future climate is a complex process driven by Earth's circulation patterns. Global Climate Models (GCMs) are typically a combination of atmosphere models, ocean models, land models, and sea ice models. The Canadian Centre of Climate Modeling and Analysis (CCCma) produced the GCM chosen for this study (Environment Canada, 2016). The CCCma has produced three versions of Coupled Global Climate Models, the third being CGCM3, which was used in this study. The major difference between CGCM3 and CGCM2 is an updated atmospheric component (Flato et al., 2014). Version 3 began with CGCM3 and was later updated to CGCM3.1, the major difference being the computer the model was run on. CGCM3.1 may be run at two different resolutions, T47 and T63 (Flato et al., 2014). T47 has a surface spatial resolution of approximately 3.75 degrees lat/long, while T63 has a surface spatial resolution of approximately 2.8 degrees lat/long (Flato et al., 2014). Each version has an higher ocean spatial resolution than surface, however T63 version has an enhanced resolution of zonal currents in the Tropics, and slightly reduced resolution in the Arctic, therefore T47 was chosen for this study. The grid that the GCM meteorological data was modeled for was centered at 120.00W, 57.52N.

CGCM3 offers multiple IPCC SRES storylines for future climate scenarios. These storylines effectively account for a wide range of vital future characteristics that may influence climate. These characteristics may be defined under two sets of divergent tendencies, one varying between strong economic values and strong environmental values, the other between increasing globalization and increasing regionalization (Carter, 2007). The storylines are summarized below (Nakićenović et al., 2000):

A1- a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.

A2- a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

B1- storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource efficient technologies.

B2- storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

Six groups of scenarios were drawn from these 4 families, with three coming from the A1 family, and one each from the A2, B1, and B2 families. The three groups from

A1 characterize developments of energy technologies: A1F1 (fossil intensive), A1T (predominantly non-fossil) and A1B (balanced across energy sources) (Carter, 2007). The A1B scenario is a middle of the road scenario in a family of rapid economic growth, with mid-century population peaks and the rapid introduction of new, more efficient technologies. This scenario predicts that by the year 2050, Earth will experience a global population of 8.7 billion, a CO2 concentration of 536 ppm, a global change in temperature of 1.6ºC, and a global sea-level rise of 17 cm (Carter, 2007). This storyline lies in the middle in terms of 2050 emission scenarios as seen in Table 1. SRES A1B was selected for this study due to its energy technologies evolution, which predicts rapid economic growth, with mid level CO_2 concentrations and a median global change in temperature and sea level.

Emissions scenario	Global population (billions)	Global GDP[1] (10^{12} US\$ a^{-1})	Per capita income ratio[2]	CO_2 concentration (ppm)	Global ΔT (°C)	Global sea-level rise (cm)
1990	5.3	21	16.1	354	0	0
2000	6.1-6.2[3]	25-28[3]	12.3-14.2[3]	367 [4]	0.2	2
2050						
SRES A1FI	8.7	164	2.8	573	1.9	17
SRESA1B	8.7	181	2.8	536	1.6	17
SRES A1T	8.7	187	2.8	502	1.7	18
SRESA2	11.3	82	6.6	536	1.4	16
SRESB1	8.7	136	3.6	491	1.2	15
SRESB2	9.3	110	4.0	478	1.4	16
IS92a	10.0	92	9.6	512	1.0	–
SRES-max	8.4	59	2.4	463	0.8	2
SRES-min	11.3	187	8.2	623	2.6	29

Table 1. 2050 responses to various emission scenarios (Carter, 2007).

Chapter 4 Results

4.1 HBV-EC Calibration Results

Figure 15 illustrates the observed and calibrated discharges in the Blueberry River for the years 1978-82 (henceforth referred to as the calibration period). As mentioned in section 3.4.3 parameters were selected to match the timing and trends of observed low-flow periods, rather than to match peak flows and volumes. The rationale behind this weighting is that water availability for withdrawal is more likely to be an issue for industry during low-flow months, as opposed to peak season. Although the flow was substantially lowered in the summer, the modeled discharge remained much greater than the winter flows. From a qualitative perspective, the observed and calibrated hydrographs appear to match quite well. The timing of peaks and spring freshet is very close, and the shapes of the hydrographs match well. Due to the influence of the parameter values assigned, peak discharge is often underestimated in the calibrated hydrograph, and should be taken into account when analyzing summer discharge in simulated periods.

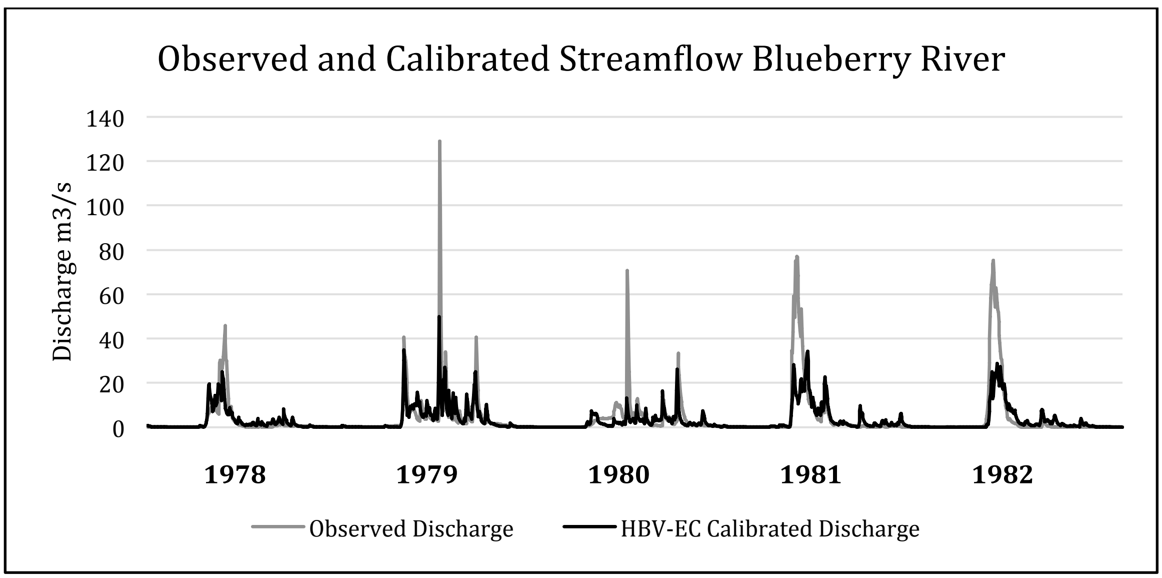

Figure 15 HBV-EC Calibrated and Observed Streamflow 1978-82.

Table 2 summarizes the results of the statistical testing performed on the calibration period, with NSE being calculated for both daily and monthly discharge. Outliers significantly influence sample NSE outcomes (McCuen et al., 2006). Observed Blueberry River discharge has numerous outliers so an NSE test was run with logarithmic values, ln NSE. This statistical test is identical to the standard NSE test, but induces sensitivity to discharge outliers by calculating Q_o and Q_m using logarithmic functions (Krause et al., 2005). Peaks are flattened and low-flows remain at the same level, increasing the sensitivity to systematic model over- or under-prediction (Krause et al., 2005).

Statistical Test		Calibration Period: 1978-82 Daily	Calibration Period: 1978-82 Monthly Mean	F. Hirshfield Calibration Results
Nash Sutcliffe Efficiency (ln NSE)		0.61	0.814	Daily – 0.79 Monthly – 0.88
Coefficient of determination R^2		0.46	0.80	0.91
RMSE (m3/s)		7.70	3.60	0.98
Mean Volume Error		0.20	0.20	9.71
Standard Deviation	$Q_{observed}$	10.19	7.30	2.2
	$Q_{modeled}$	5.28	4.45	2.07

Table 2 Quantitative testing results based on daily and monthly discharge data from model calibration.

The quantitative testing summarized in Table 2 shows the correlation between modeled and observed discharge during the calibration period. Mean monthly data has a stronger correlation than that of the daily data. Hirshfield (2010) used similar statistical tests to compare their observed and modeled discharges, and the results of this testing are included as a reference (Table 2). The first thing to note about my study is the decrease in the standard deviation between observed and modeled discharge. Having a lower standard deviation indicates that flow is more uniform throughout the year, without great changes in peak discharge. Singh (2004) suggests that model calibration is satisfactory if

NSE values for daily flow are ≥ 0.70, or monthly flow is ≥ 0.8. My daily calibration fell slightly below the threshold, but monthly calibration was sufficient (0.61 and 0.814 respectively).

R^2 testing was around 50 percent for daily data and measured 80 percent for mean monthly. The RMSE indicated on average 7.7 m^3/s more discharge through the observed period than the modeled, however when taken as a monthly mean this is lowered to 3.60 m^3/s. RMSE is considered low if it is half the standard deviation. The monthly RMSE values were less than half the observed standard deviation, therefore error is considered to be low. MVE was the same for daily and monthly data, and was 0.05 above the standards suggested by Hummel et al (2003). The standard deviation of the observed flow was greater than that of the modeled, indicating that modeled flow predicts a more uniform discharge throughout the year, with lower peaks, as was expected from the parameters selected. Due to the local effects on day-to-day discharge, daily data is much more difficult to replicate than monthly. Monthly data better summarizes the agreement between the two discharges, and justifies the calibration. The results of the statistical testing indicate that the HBV-EC calibration sufficiently capture the low flow and monthly trends of the observed data in the Blueberry River, and are within acceptable error to justify the agreement between the modeled, and observed hydrographs.

4.2 Future Climate under A1B Emission Scenario

Daily climate data was compiled from the GCM 2046-2065 data package (Environment Canada, 2016) in order to determine discharge in the Blueberry River under various climate scenarios. Data from the GCM package included daily mean precipitation, temperature, snowfall, monthly temperature and evaporation, as well as daily surface snow depth. Tables 4 and 5 in the Appendix summarize both observed and GCM simulated precipitation, snowfall and temperature into mean monthly values. Trends in mean monthly precipitation and temperature are plotted in Figures 16 and 17. For descriptive purposes, winter months are grouped as January-March, spring as April-June, summer as July-September, and fall as October-December.

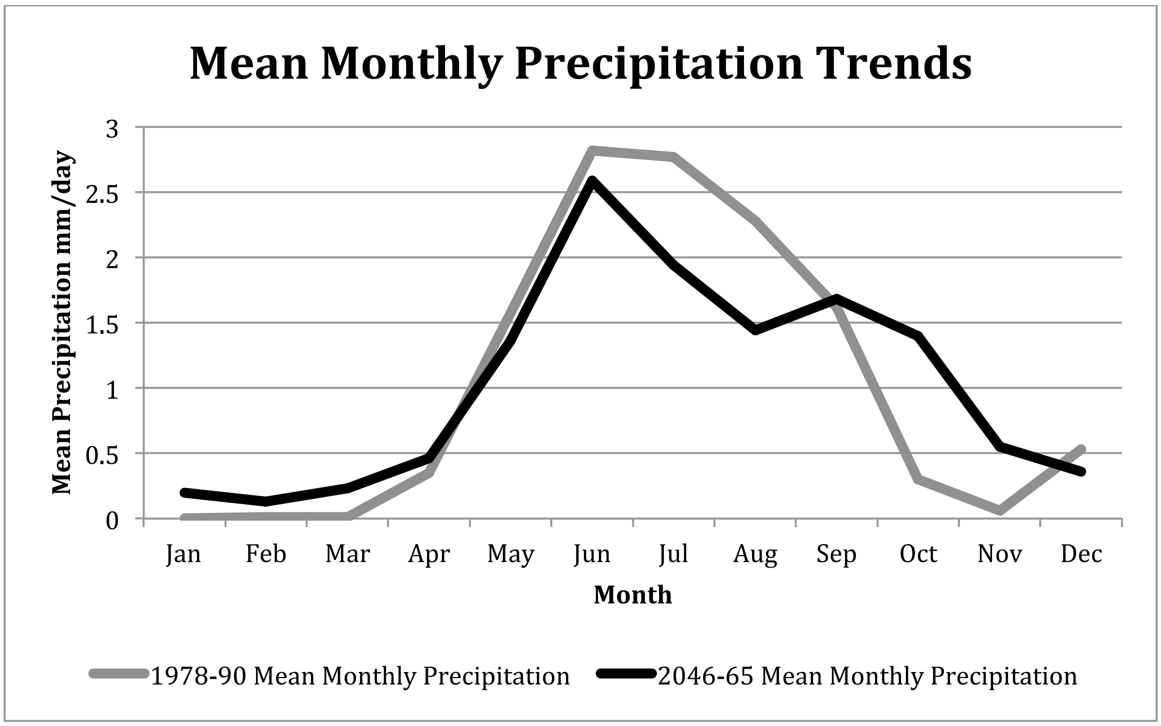

Figure 16 Mean Monthly Precipitation Comparison (mm/day) between 1978-90 Historic and 2046-2065 Simulations.

Mean annual precipitation is similar for observed and projected periods (both averaging 1.03mm/day), however monthly precipitation fluctuates. Under the SRES A1B trend, precipitation sharply drops off in late spring/early summer, but rebounds in late summer/early fall, when observed precipitation is steadily declining. Winter months also observe a ~0.2 mm/day increase in precipitation in the SRES A1B model.

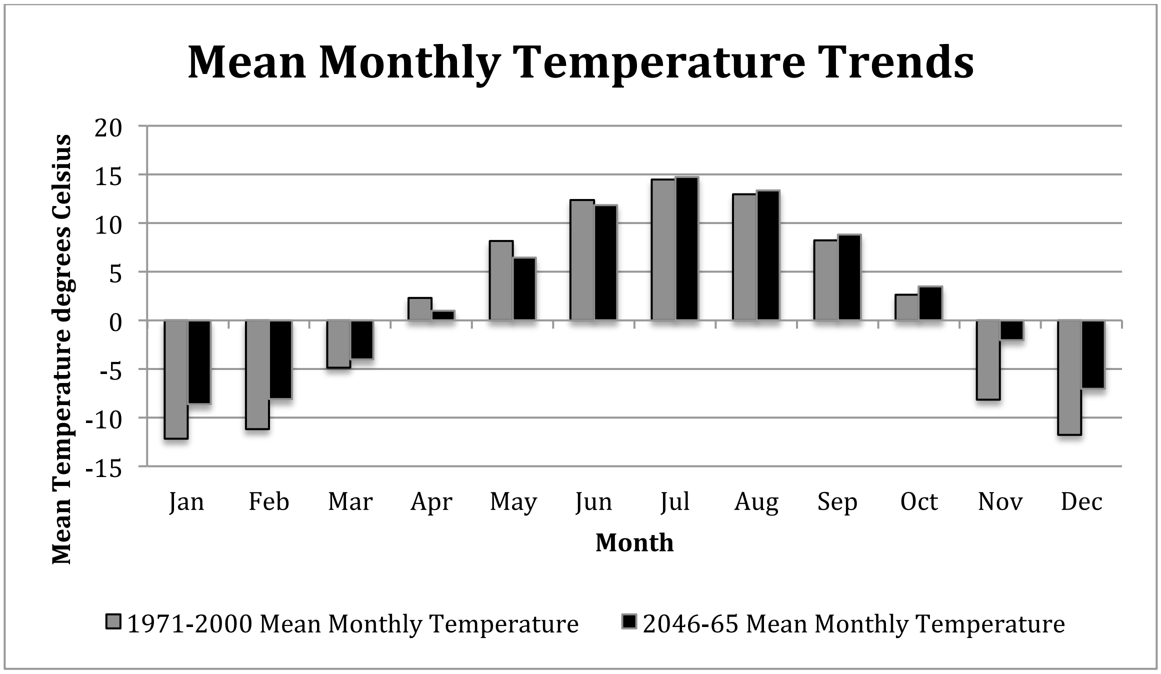

Figure 17 Mean Monthly Temperature Comparison (degrees Celsius) between 1971-2000 Historic and 2046-65 Simulated Periods.

Historic temperature data from the Wonowon climate station was available between the years 1971-2000. The mean monthly temperature for the historic, and simulated 2046-65 periods was compared to find an annual change in temperature of +1.51 °C. This temperature change applies for the 3.75 degree lat/long grid surrounding the Blueberry Basin. Figure 17 graphs the monthly variation in temperature, demonstrating the seasonality changes. Winter, summer and fall months are projected to be warmer under the emission scenario simulated than what has historically been observed, while spring months are projected to be cooler than observed. This has the potential to influence melting and discharge, and will be explored further in the coming sections.

4.3 Future Streamflow under A1B Emission Scenario

Meteorological data from the GCM period was input into HBV-EC under the parameters defined in the calibration and run to simulate discharge under various climate conditions. HBV-EC only permits meteorological data to be run for individual years, therefore five years, equally distributed through the GCM period were simulated. As mentioned in section 3.4.2, HBV-EC is not compatible with daily mean meteorological data therefore a "mean discharge" could not be produced from the software. The following figure demonstrates the simulated discharge from 2046 to 2065; summaries of the period, and each simulated year are included below.

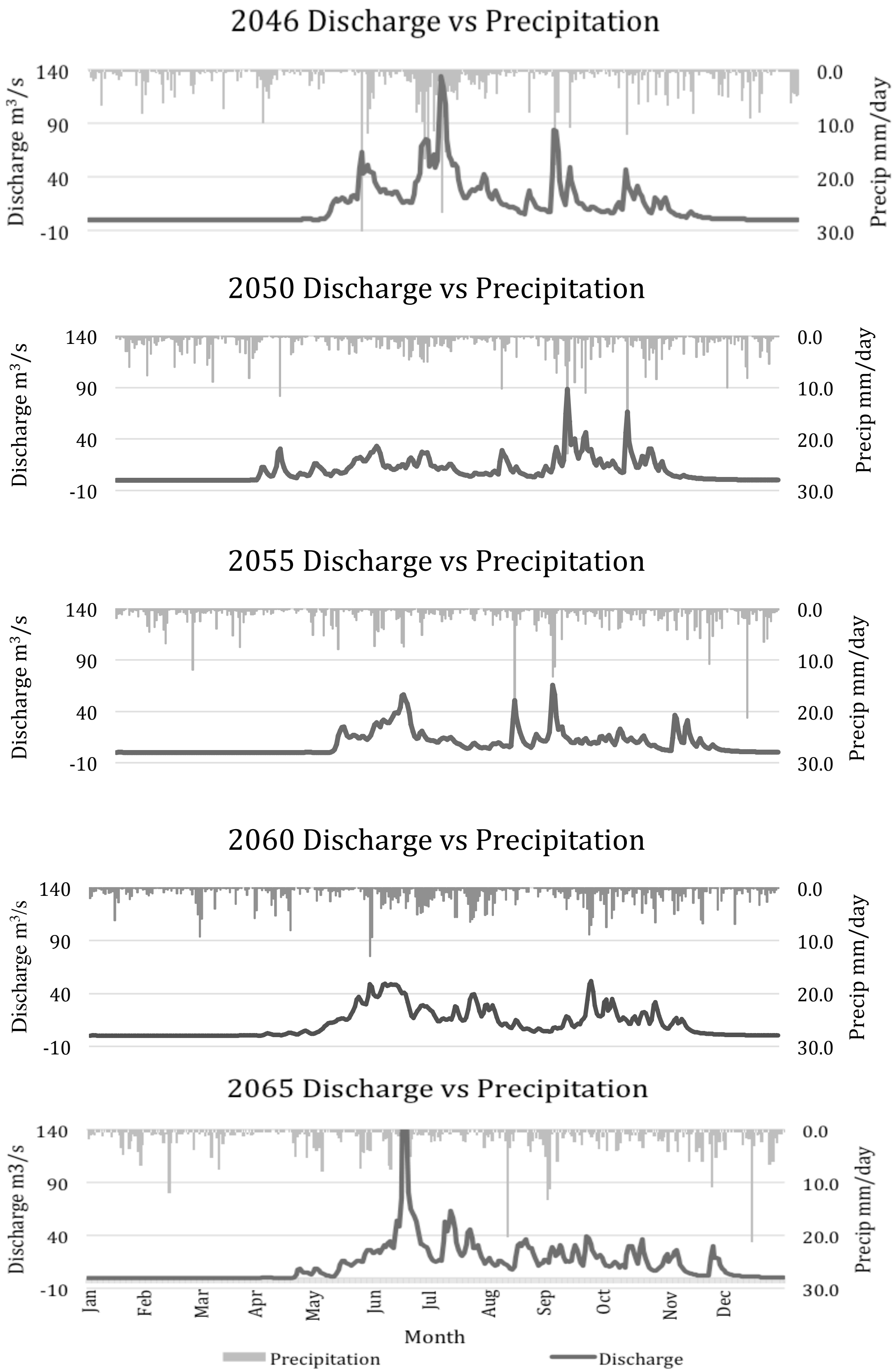

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Figure 18 Hydrograph of simulated discharges, compared alongside daily precipitation.

The most noticeable difference between the simulated hydrographs in Figure 18 and the observed hydrographs from the historic period in Figure 15 is timing of peaks. The historic period observed minimal flow in the early winter months, a high volume spring freshet, and a moderate flow through the summer, into the fall. The simulated hydrographs demonstrate more variance in peaks, and a longer discharge season with peaks commonly approaching 40 m^3/s in the fall. The following summaries break down individual years simulated, which demonstrate the responsiveness of the stream to specific climate conditions. It should be noted that although data was simulated for individual years, this study does not serve to predict the climate of any individual year. Instead, this analysis aims to evaluate how the Blueberry River may respond to a range of possible climates. While the simulated climate may not occur in the year it was assigned by the GCM, it posses a possible scenario that the watershed may undergo sometime in the future, and by forecasting the discharge these possible scenarios, we may observe a range of responsive flows.

The Blueberry River Basin in the year 2046 was simulated to begin with an initial snow pack of 48.5 cm. Mean daily temperature predominantly remained below freezing until early April, and returned to sub zero conditions in mid-October. 2046 projected the greatest annual precipitation of all simulated years (470.53 mm) largely owing to heavy precipitation events in late May, early July, and early September. These peak precipitation events correlate closely to peaks in discharge. The climatic conditions resulted in streamflow beginning in early May, peaking in early July, and declining from

October onwards, with very minimal flow after November. The hydrograph indicates a decline in flow in late summer, with a second peak in September.

The year 2050 began with an initial snowpack of 42.1 cm. Mean daily temperature remained sub 0 ºC until early March, and fell below freezing once again in early November. Unlike 2046, the summer months in 2050 are predicted to be quite dry, which is more representative of the mean climate predicted. Discharge simulated from 2050 climate data (Fig. 18) indicates flow beginning in mid-March, and not peaking until September. This spring freshet is the earliest of any of the simulations that were run. Of interest, the year 2050 simulated the greatest March flow of any simulated year, with a total discharge of 47 million m^3 (~15 percent of the annual discharge for 2050). This abnormal spring freshet may be attributed to the early melting of snowpack, onset by early season temperatures exceeding 0 ºC. Early season melt, accompanied by minimal summer precipitation, results in a relatively modest flow through the late spring and summer, rarely exceeding 30 m^3/s, until discharge peaks in late summer/ early fall, when precipitation returns. This hydrograph predicts a similar late season decline in discharge to that seen in 2046. The period of peak discharge is much later in 2050 than other years simulated.

The year 2055 is simulated to begin with an initial snow pack of 66.1 cm. The GCM data simulated an unseasonably cold April, with temperatures failing to consistently exceed 0 ºC before early March. Much like 2050, the summer months are quite dry, with limited precipitation and flow between mid-June to mid-August. 2055 registered the least amount of annual precipitation, of all years simulated (296.84 mm). Simulated discharge indicates flow beginning in early May, with three peaks in mid-June, mid-August and early-September. Flow declines September to November, however an additional late season peak is seen in early-November.

The year 2060 is simulated to begin with an initial snow pack of 99.1 cm. Temperatures remain below freezing until early March, and remain around freezing until April. Temperatures dip below freezing once more in late October / early November. Streamflow is simulated to be very minimal beginning in early April, and exceeds 10 m^3/s for the first time in early-May. Summer peak flow arrives in late-May to mid-June. Flow falls below the mean between mid-August to October, and declines in November much like we saw in previous years.

The final year simulated in HBV-EC begins with an initial snow pack of 78.5cm. Temperatures remain below freezing until early April, and return below freezing in late October. Annual precipitation was quite high totaling 451.76 mm. This climate scenario produces streamflow beginning in late-April, peaking in mid-June, and maintaining rather high flow through the summer and into the fall. 2065 simulations produced the greatest volume of annual flow (445 million m^3), and the highest peak of all simulated years (213 m^3/s). For comparison, the Observed mean annual volume was 615 million m^3, and the Calibrated mean annual volume was 490 million m^3. This indicates that under the climate conditions summarized above, mean annual flow is projected to decline.

Chapter 5- Discussion

The NorthEast Water Tool (NEWT) was developed to support the decision-making process for short-term water use approvals in Northern British Columbia. The monthly and annual average runoff is calculated at numerous locations on rivers and lakes in the region, creating a 30-year average. To gauge the volume of water allocated for withdrawal, NEWT also queries a complete list of short-term water use approvals and licences. The environmental flow guidelines used in the province of Alberta (Locke and Paul, 2011), have been modified to align with the *BC Ministry of Environment's* Environmental Flow Needs (EFN) through the Water Sustainability Act. EFN designates that a minimum of 85 percent of natural streamflow must be maintained at all times, to sustain natural ecological function. EFN may be altered slightly depending on the amount of annual flow, and the ratio of winter flow to annual (OGC, 2016). EFN can range from 85-95 percent, however for the purpose of this analysis, it is assumed to be 95 percent for winter months (Dec – Mar), and 85 percent otherwise (Apr – Nov).

Water licences are classified in NEWT based on the volume and location of the withdrawal within the basin. The Blueberry Basin (Upstream of Aitken Creek) currently sources forty-two withdrawal sites, potentially totaling 564 959 m^3 of water to be withdrawn per year. Approximately 76 thousand m^3 of this is drawn from springs, or ponds within the basin. The Blueberry or Aitken Rivers are currently sources to ten direct domestic withdrawals, totaling an annual withdrawal approval of 250 059 m^3. These ten direct withdrawal sites are primarily used for agriculture and dust control. There are an additional nineteen Section 8 water approvals (short term) sourced from the

Blueberry River, which are used for water source dugouts. Three energy companies, Storm Resources, Canadian Natural Resources Limited, and Conoco Phillips own these short-term approvals. Between industry and domestic use, the total annual allocations that directly withdraw from Blueberry River or Aitken Creek equates to 488 836 m^3/year, which was the total volume used in calculating monthly allocations.

In order to determine the difference between available water for withdrawal under ENF regulations and the amount currently allocated via water licences, a series of tables were created in the Appendix. Daily discharge data was summed by month for the observed and calibrated periods (1978-82) as well as for simulated years 2046, 2050, 2055, 2060, and 2065 (Table 6.1). Available water for withdrawal under ENF regulations was then calculated as a percentage of total monthly flow: 5 percent of monthly discharge for winter months, and 15 percent for non-winter months (Table 6.2). Current (2016) annual allocations were then divided uniformly by month, regardless of winter or non-winter flow, simulating an assumption of constant demand for withdrawal throughout the year. By distributing current total allocations over a 12 month period, it was determined that 40 736 m^3/month would be allocated to be withdrawn from the stream (Table 6.3). Monthly allocated flow (Table 6.3), was then subtracted from monthly EFN-regulated available flow (Table 6.2) to determine if withdrawal demands could be met on a monthly basis (Table 6.4). All tables are available in the Appendix.

Based on results from Table 6.4, February of the observed and calibrated periods (1978-82) would not have met the withdrawal demands of current (2016) equally distributed annual allocations. The observed discharge from the historic period was approximately 2 500 m^3 short of demands, and the calibrated discharge from the historic period was approximately 31 000 m^3 short of the demands of current allocations. The remaining winter months in the observed and calibrated periods predicted ~40 000 m^3/month of excess flow after withdrawal. Of the five simulated years, under current approved allocations, all years would experience some degree of over-withdrawal.

For the simulated year 2046, the model predicts low-flow conditions from January to March, with ~130-640 m^3/month being available for withdrawal. This is significantly short of the 40 736 m^3/month that would be required under equally distributed monthly allocations.

For the year 2050, the model predicts extremely limited flow in January and February, which could not sustain any monthly withdrawal. March and December would not undergo water shortages, and all summer months could support 15 percent withdrawal.

For the years 2055, 2060 and 2065, the model predicts low flow from January to March. Flow narrowly exceeds the allocated 40 736 m^3 in April of 2055, and December of 2060. All remaining months would sustain allocation demands.

Of the years simulated, most winter-months are expected to experience difficulty meeting allocated withdrawals. The months of January and February of every year simulated are predicted to experience a low-flow and negative net between available, and approved volume for withdrawal. December is not expected to experience over-allocation for any simulated year, however December 2046 is only projected to maintain 4 065 m^3 additional flow, post allocation.

In the event withdrawal was stopped for the low flow months identified in Table 6.4 once minimum EFN regulations were met (5 percent of allotted flow was withdrawn), an analysis was done to determine which months could withstand further withdrawal, to meet the demands of the annual approved allocations. The remaining volume of water that was unable to be withdrawn in low flow months was summed, and equally distributed across the remaining positive net months. From this I projected which months would be capable of withstanding further withdrawal, while maintaining 95 percent (winter) or 85 percent (non-winter) flow. These findings are presented in Table 6.5 in the Appendix. The amount of monthly redistribution varied by year, and was contingent on how much water could be withdrawn by the low-flow months before reaching EFN minimums. The maximum volume redistributed was in 2065, which required an additional 13 467 m^3/month to be withdrawn to cover what was not withdrawn between January and March. Post redistribution, only two months were unable to meet the withdrawal demands while staying above EFN regulations. These months were April of 2055, and December of 2046.

An additional analysis was done to simulate the effects of increasing water demand in the Blueberry River Basin. Hayes (2012) states that the Montney Basin is expected to double or triple the rate of production by the year 2020. Increasing production would result in a greater need for water; therefore by doubling the current (2016) annual allocations in the Blueberry River Basin, predictions for water availability under increased production scenarios may be made. For the purpose of identifying periods of limited flow, 2016 annual allocations were doubled and then distributed equally by month, regardless of winter or non-winter flow, once again simulating an assumption of constant demand for withdrawal throughout the year. Through this distribution, it was determined that 81 472 m^3/month would be allocated to be drawn from the river. Table 6.6 in the Appendix summarizes the findings of these comparisons.

Doubling the current allocations predicts significant over-allocations in the Blueberry River, in both historic and simulated years, especially in winter months. All measured years observe a low flow in Jan-Mar, with the exception of March 2050. December of 2046 and 2050 is also projected to fail to meet the monthly withdrawal requirements, with December of 2060 coming within 475 m^3 of the limit. April 2055 is the only non-winter month to observe over-allocation, with an additional 28 662 m^3 being needed to meet the withdrawal demand. This analysis is perhaps the best indicator of water availability in the Blueberry River. It has been established through current (2016) allocations that winter months in the simulated period would likely experience difficulty meeting withdrawal demands, assuming equally distributed monthly allocations. By doubling the annual allocations however, we only observe one non-winter month that would fail to meet these demands, demonstrating the magnitude of reserve the Blueberry River has to accommodate growth in water demand in the area.

To understand the scale of the change in streamflow, consider that for the historic period (1978-82), November produced the *lowest* non-winter flow at 5 550 854 m^3, which would have supported a maximum allocation under EFN regulations of 832 628 m^3/month or *20 times* the current allocation of 40 736 m^3/month. This is nearly twice the total annual allocation currently administered in the watershed. In contrast, the model predicted that in 2055, the lowest flow in a non-winter month would occur in April at 52 810 m^3 which would only just meet the current allocation and could not withstand significant increase in demand. Flow in this simulated month is greater than the preceding winter months (Jan-Mar 2055), however is uncharacteristically low for typical April flow. The climate model simulated April 2055 to have unseasonably cold temperatures (sub 0^{o}C all month), which likely caused this low flow. While the nature of climate modeling does not permit us to assume these climate conditions will in fact be replicated, it does permit the user to observe how the stream would react to conditions similar to those simulated.

It should be noted that while simulated non-winter months are projected to experience very minimal instances of water shortage under current allocations, available water is nevertheless substantially less, as indicated by the difference in mean annual flow between simulated years and the calibrated period. It should also be noted however, that the model was calibrated to forecast the more-at-risk winter-month flow more accurately, and therefore the non-winter projections may contain significant underestimations.

While water is a vital component of the hydrocarbon extraction process, limited winter flow in the Blueberry River under future scenarios does not mean that development must stop in this region. The purpose of modeling for such an event is to provide industry and regulators with an additional tool to aid in the planning for growth and development in the region. The calculations made in Tables 6.3 - 6.7 in the Appendix assume that equal withdrawals would be made every month, as opposed to "stock piling" water in high volume months. While this may not represent the practice that would likely be followed, it effectively demonstrates which months would not be able to meet withdrawal demands, and therefore aids licence holders to plan when withdrawal should occur. It should also be noted, that the withdrawals awarded in short-term licences are often not withdrawn to their full allocation. This being said, it is important to model for complete withdrawal, in the event the allocated volume is fully withdrawn. From the results of the study, I propose that changes to hydrology in the Blueberry River Basin are plausible in the next 50 years. The magnitude of these changes however, is difficult to predict with a high degree of certainty, due to model limitations.

Quantifying error and uncertainty in discharge for the watershed model is difficult, especially for future scenarios. At current levels of development, the inability to state simulated results with great confidence makes forecasting future streamflow incompatible with policy formation (Lui et al, 2008). In an effort to bring modeling to a level that would support policy formation, further research is required to quantify the uncertainty in hydrologic modeling. While the above noted uncertainty does limit the immediate applicability of the results in this study, the methodology shows promise of merit, and is worthy of further development. In addition, the trends simulated by HBV-EC seem plausible and add to our knowledge about forecasting for water availability under future climate scenarios.

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Appendix-

Table 3- HBV-EC parameter values to study the Blueberry River Basin, as well as HBV-EC default, and Hamilton et al., 2001 parameter values.

	Parameter	Default	Blueberry River	Hamilton et al., 2001
Routing				
Parallel	Runoff FRAC	0.7	0.8	0.34
	Runoff KF	0.2	0.3	0.013
	Runoff Alpha	0.1	0.3	0.49
	Runoff KS	0.05	0.05	0.00148
	Fast Reservoir Q	0	0	?
	Slow Reservoir Q	0	0	?
Climate				
Atmosphere	RFCF	1.0	0.977	0.977
Atmosphere	SFCF	1.0	1.27	1.27
Atmosphere	PGRADL	.0001	.0022	.0022
Atmosphere	PGRADH	0	0	?
Atmosphere	EMID	5000	5000	?
Atmosphere	TLAPSE	0.0065	0.005	0.005
Atmosphere	TT	0	0	-.727
Atmosphere	TTI	2	0	0
Atmosphere	EPGRAD	0.0005	0.0003	0.0003
Atmosphere	ETF	0.5	0	0
Forest	TFRAIN	0.8	0.838	0.838
Forest	TFSNOW	0.8	0.845	0.845
Snow	AM	0	0.7	?
Snow	TM	0	2	1.7
Snow	CMIN	2	1.65	1.65
Snow	DC	2	2.55	2.55
Snow	MRF	0.7	0.706	0.706
Snow	CRFR	2	1.04	1.04
Snow	WHC	0.05	0.1	0.1
Snow	LWR	2500	4000	4000
Soil	FC	200	200	200
Soil	Beta	1	1.81	1.81
Soil	LP	0.7	0.599	0.599
Glacier	MRG	2	2	?
Glacier	AG	0.05	0.05	?
Glacier	DKG	0.05	0.05	?
Glacier	KGMIN	0.05	0.05	?
Glacier	KGRC	0.7	0.7	?

Table 4- Mean monthly precipitation, snowfall and temperature data for calibration period 1978-90, Wonowon Climate Station.

1978-90	Mean Precipitation mm/day	Mean Snowfall cm/day	Mean Temperature ºC
Jan	0.00	0.73	-12.5
Feb	0.01	0.85	-11
Mar	0.01	0.89	-5.4
Apr	0.35	0.68	2.5
May	1.57	0.40	8.1
Jun	2.82	0	12.4
Jul	2.77	0	14.4
Aug	2.28	0	12.9
Sep	1.62	0.15	8.3
Oct	0.30	0.77	2.6
Nov	0.06	0.88	-8.5
Dec	0.53	0.66	-12.1
Mean	**1.03**	**0.50**	**0.98**

Table 5- Mean monthly precipitation, snowfall and temperature data for CGCM3.1, A1B scenario.

2046-65	Mean Precipitation mm/day	Mean Snowfall cm/day	Mean Temperature ºC
Jan	0.20	1.33	-8.63
Feb	0.13	1.14	-8.10
Mar	0.23	0.78	-4.04
Apr	0.46	0.41	0.98
May	1.36	0.07	6.45
Jun	2.59	0.00	11.87
Jul	1.94	0.00	14.72
Aug	1.44	0.13	13.34
Sep	1.68	0.02	8.82
Oct	1.40	0.34	3.47
Nov	0.55	0.98	-2.00
Dec	0.36	1.18	-7.05
Mean	**1.03**	**0.53**	**2.49**

Table 6.1 Monthly Discharge m^3 Blueberry River Basin-

	Historic	Calibrated	2046	2050	2055	2060	2065
Jan	1.31E+06	1.62E+06	8.92E+03	2.87E-01	1.77E+05	1.43E+05	1.58E+04
Feb	7.64E+05	1.97E+05	1.28E+04	4.87E-01	1.35E+04	1.70E+04	2.51E+03
Mar	1.36E+06	1.07E+06	2.67E+03	9.84E+06	8.00E+03	3.14E+05	1.63E+03
Apr	9.72E+07	5.67E+07	6.25E+05	2.26E+07	3.52E+05	4.88E+06	5.69E+06
May	2.71E+08	1.61E+08	6.80E+07	4.69E+07	5.31E+07	5.64E+07	3.36E+07
Jun	8.17E+07	7.89E+07	1.00E+08	4.18E+07	6.58E+07	9.29E+07	1.37E+08
Jul	7.08E+07	6.39E+07	1.13E+08	2.13E+07	2.13E+07	5.94E+07	8.05E+07
Aug	2.09E+07	4.73E+07	5.43E+07	2.98E+07	5.06E+07	2.68E+07	5.11E+07
Sep	4.84E+07	4.97E+07	4.02E+07	7.48E+07	3.46E+07	4.61E+07	5.80E+07
Oct	1.36E+07	1.61E+07	4.63E+07	5.31E+07	2.73E+07	5.22E+07	4.45E+07
Nov	5.55E+06	1.22E+07	6.15E+06	6.67E+06	2.97E+07	1.63E+07	2.85E+07
Dec	2.50E+06	1.73E+06	8.96E+05	1.13E+06	2.54E+06	1.64E+06	4.16E+06
Total:	6.16E+08	4.90E+08	4.30E+08	3.08E+08	2.85E+08	3.57E+08	4.43E+08

Table 6.2 Volume Available for Withdrawal Under Max EFN Regulations m^3, 5 or 15 percent of Table 6.1

	Historic	Calibrated	2046	2050	2055	2060	2065
Jan	6.56E+04	8.11E+04	4.46E+02	1.44E-02	8.85E+03	7.16E+03	7.92E+02
Feb	3.82E+04	9.85E+03	6.40E+02	2.44E-02	6.77E+02	8.52E+02	1.25E+02
Mar	6.79E+04	5.36E+04	1.33E+02	4.92E+05	4.00E+02	1.57E+04	8.17E+01
Apr	1.46E+07	8.51E+06	9.37E+04	3.39E+06	52810.30	7.33E+05	8.54E+05
May	4.07E+07	2.41E+07	1.02E+07	7.04E+06	7.96E+06	8.45E+06	5.04E+06
Jun	1.23E+07	1.18E+07	1.50E+07	6.27E+06	9.87E+06	1.39E+07	2.06E+07
Jul	1.06E+07	9.59E+06	1.69E+07	3.20E+06	3.19E+06	8.91E+06	1.21E+07
Aug	3.13E+06	7.09E+06	8.14E+06	4.47E+06	7.59E+06	4.03E+06	7.67E+06
Sep	7.26E+06	7.45E+06	6.03E+06	1.12E+07	5.19E+06	6.91E+06	8.71E+06
Oct	2.04E+06	2.41E+06	6.94E+06	7.97E+06	4.10E+06	7.84E+06	6.68E+06
Nov	8.34E+05	1.82E+06	9.23E+05	1.00E+06	4.46E+06	2.45E+06	4.27E+06
Dec	1.25E+05	8.65E+04	4.48E+04	5.64E+04	1.27E+05	8.19E+04	2.08E+05
Total:	9.17E+07	7.30E+07	6.43E+07	4.51E+07	4.25E+07	5.34E+07	6.61E+07

Table 6.3 Uniform Distribution of Total Annual Allocations m^3-

	Historic	Calibrated	2046	2050	2055	2060	2065
Jan	40736	40736	40736	40736	40736	40736	40736
Feb	40736	40736	40736	40736	40736	40736	40736
Mar	40736	40736	40736	40736	40736	40736	40736
Apr	40736	40736	40736	40736	40736	40736	40736
May	40736	40736	40736	40736	40736	40736	40736
Jun	40736	40736	40736	40736	40736	40736	40736
Jul	40736	40736	40736	40736	40736	40736	40736
Aug	40736	40736	40736	40736	40736	40736	40736
Sep	40736	40736	40736	40736	40736	40736	40736
Oct	40736	40736	40736	40736	40736	40736	40736
Nov	40736	40736	40736	40736	40736	40736	40736
Dec	40736	40736	40736	40736	40736	40736	40736
Total:	488836	488836	488836	488836	488836	488836	488836

Table 6.4 Remaining Water (Volume Available – Volume Allocated) m^3-

	Historic	Calibrated	2046	2050	2055	2060	2065
Jan	24897	40371	-40290	-40736	-31887	-33581	-39944
Feb	-2556	-30889	-40096	-40736	-40059	-39884	-40611
Mar	27135	12898	-40603	451177	-40336	-25061	-40655
Apr	14540054	8468620	52950	3350946	12074	691914	813046
May	40679195	24053091	10159390	7000334	7917267	8414056	4994411
Jun	12221134	11796553	14975948	6232762	9828611	13892294	20546671
Jul	10578286	9547351	16904598	3155528	3148008	8866627	12036660
Aug	3087847	7047910	8099999	4429468	7545761	3984860	7628844
Sep	7219015	7409432	5992938	11174100	5145656	6867716	8664405
Oct	1995072	2373879	6903335	7924320	4058844	7796686	6636930
Nov	791892	1783792	881803	959570	4418457	2410783	4226814
Dec	84349	45776	4065	15678	86458	41212	167217
Total:	91246321	72548785	63854037	44612410	42048854	52867624	65593789

Table 6.5. Redistributed Flow m^3-

	Observed	Calibrated	2046	2050	2055	2060	2065
Jan	24665	37563	0	0	0	0	0
Feb	0	0	0	0	0	0	0
Mar	26903	10090	0	443029	0	0	0
Apr	14539822	8465812	39507	3342799	-402	680967	799578
May	40678962	24050283	10145947	6992187	7904792	8403109	4980943
Jun	12220902	11793745	14962504	6224615	9816135	13881347	20533203
Jul	10578054	9544543	16891155	3147381	3135532	8855680	12023193
Aug	3087614	7045102	8086555	4421320	7533286	3973913	7615377
Sep	7218783	7406624	5979495	11165952	5133180	6856769	8650938
Oct	1994840	2371071	6889892	7916173	4046368	7785739	6623462
Nov	791659	1780984	868360	951422	4405982	2399836	4213346
Dec	84117	42968	-9378	7531	73982	30264	153749

Table 6.6. Remaining Flow After Doubling Allocations m^3-

	Observed	Calibrated	2046	2050	2055	2060	2065
Jan	-15839	-365	-81027	-81473	-72624	-74317	-80681
Feb	-43293	-71625	-80833	-81473	-80795	-80620	-81347
Mar	-13601	-27838	-81339	410440	-81072	-65797	-81391
Apr	14499318	8427884	12214	3310210	-28662	651178	772310
May	40638459	24012355	10118654	6959598	7876531	8373320	4953675
Jun	12180398	11755817	14935211	6192026	9787875	13851558	20505935
Jul	10537550	9506615	16863862	3114792	3107272	8825891	11995924
Aug	3047110	7007174	8059262	4388731	7505025	3944124	7588108
Sep	7178279	7368695	5952202	11133363	5104920	6826980	8623669
Oct	1954336	2333143	6862599	7883584	4018108	7755950	6596194
Nov	751155	1743056	841067	918833	4377721	2370047	4186077
Dec	43613	5040	-36671	-25058	45721	475	126480
Total:	90757485	72059949	63365201	44123574	41560018	52378788	65104953